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FULL-SCALE DESULFURIZATION OF STACK GAS BY DRY LIMESTONE INJECTION. VOLUME III. APPENDICES I THROUGH L

F. E. Gartrell

Tennessee Valley Authority

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The report gives results of a test program of dry limestone injection, demonstrated on a 150-Mw pulverized-coal-fired boiler at TVA's Shawnee Plant. The program included: equipment shakedown, dust distribution studies, process optimization, and long-term injection trials. It identified major process variables; evaluated distribution of lime dust in the boiler, effect of operating variables on distribution, and sulting effects on SO2 removal; evaluated the sensitivity of SO2 removal to key operating and process variables; evaluated conditions for optimum SO2 removal; studied process effects on boiler operation and maintenance, on solids collection equipment, and on water quality; and completed a process economics study. The program is discussed in context with previous investigations and EPA-sponsored support activities. Appendices contain test program detail results and results of EPA support projects. Because of low SO2 removal efficiencies and the potential for major reliability problems, it does not appear that dry limestone injection will play an important role in controlling SO2 emissions from power plants.

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VOLUME III -
APPENDICES I THROUGH L

by
Tennessee Valley Authority
Chattanooga, Tennessee

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CONVERSION TABLE

EPA policy is to express all measurements in Agency documents in metric units. When implementing this policy results in undue cost or difficulty in clarity, the National Environmental Research Center-Research Triangle Park (NERC-RTP) provides conversion factors for the particular nonmetric units used in the document. For this report these factors are:

British		Metric
Multiply	By	To Obtain
feet	3.0480×10^{-1}	meters
feet^2	9.29×10^{-2}	meters^2
feet/sec.	3.0480×10^{-1}	feet/sec.
feet^3 /min.	4.720×10^{-1}	liters/sec.
grains (troy)	6.48×10^{-2}	grams
grains/dry s.c.f. @ 70° F	2.464	grams/meter^3 @ 0° C
gallon	3.785	liters
inch	2.5400×10^{-2}	meters
micron	1.0×10^{-6}	meters
ounce (troy)	3.1103×10^{1}	grams
pound	4.536×10^{-1}	kilograms
pound/in.^2	7.03×10^{-2}	kg/cm^2
quart	9.463×10^{-1}	liters
tons/hr.	2.520×10^{-1}	kg/sec.

APPENDIX I

Limestone Factors

Section A	Reactivity with Sulfur Oxides
Section B	Availability in the United States
Section C	Definitions
Section D	References

APPENDIX I
LIMESTONE FACTORS

The author discusses those factors which experimentation identified as most important to the process. These include limestone type, chemical form of the additive, particle size, calcination temperature, and the effects of catalysts.

Discussed are the activities of the following organizations:

Illinois State Geological Survey
Tennessee Valley Authority
Babcock & Wilcox
Peabody Coal Company
Environmental Protection Agency

Included are recommendations for additive preparation for the dry limestone injection process.

Regarding availability, the author discusses the potential demand for limestone, its distribution, mining, and production as well as the supply/demand relationship of carbonate rocks for pollution control.

Transportation and costs for limestone use at power plants are covered.

Recommendations for application to dry limestone injection and other limestone-based processes indicate the use of the available information for study by a potential user.

Section A
Reactivity with Sulfur Oxides

I. Introduction and Objectives

The activities of the Research Laboratory Branch, Control Systems Division in support of the high priority development of throw-away processes, have been directed toward specific areas relating to the limestone processes. During the last 2-1/2 years major emphasis has been on acquiring information on the dry injection process which would be required for application of the process on a wide scale. Earlier, a little was known about the mechanism and rate of reaction between limestone and sulfur oxides, and differences between limestones had not been related to their potential reactivity. This information was vital for optimization of the process. Limestone injected into a power boiler must calcine (evolve CO_2 to become lime) and react with most of the sulfur oxides present—all within 2 seconds or less. If limestone is injected too close to the highest temperature combustion zone, the lime produced will be deadburned and unreactive. If the limestone is injected higher than or farther from this zone, the residence time for the lime particles in the zone of the boiler favoring reaction with sulfur oxides will be seriously reduced. The overall objective of this activity was to support the full scale process optimization at the TVA Shawnee Steam Plant by recommending limestone type, particle size, and other sorbent and process parameters.

II. Approach

The general approach toward meeting the first objective was to measure reaction rates and capacities of limestones and then correlate results with their mineralogical, petrographic, and chemical analyses. Bench scale calcination and sulfation tests were conducted in-house in fixed-bed and differential reactors and under contract in a standard laboratory thermogravimetric-analyzer apparatus by TVA and a dispersed phase reactor by Battelle. Under contract with Illinois State Geological Survey (ISGS) and TVA, petrographic and electron microscopy, X-ray, and additional chemical analyses were performed on raw, calcined, and sulfated samples from the bench-scale tests. Correlations between results of these analyses and the bench-scale reactivity results were then attempted. Pilot-scale tests were conducted under contract with Babcock & Wilcox and Peabody Coal at conditions simulating, as closely as possible, actual furnace injection conditions. These tests were conducted for comparison with the bench-scale data and limestone reactivity correlations developed.

The approach toward the second objective, determining the characteristics of dead burning, was to conduct full-scale tests with pure additive in an oil-fired furnace. Pure additive and the oil-fired furnace were selected in order to avoid possible chemical changes during dead burning which can occur by reaction of CaO with oxides of silicon, iron, and aluminum present as a limestone impurity and in coal fly ash. Injection with the fuel was

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selected to maximize residence time at high temperatures for fast calcination and sulfation. With this approach it was possible to characterize the phenomena of dead burning specifically in terms of physical changes and their relationship to reactivity with SO_2. Concurrent with this activity, methods for testing the degree of dead burning (loss of CaO reactivity) were evaluated through literature searches, analysis of various chemical and physical properties of different limestones calcined at a range of temperatures, and laboratory testing. More promising tests were applied to samples from pilot scale tests by Babcock and Wilcox and from early injection tests at the TVA Shawnee Steam Plant.

III. Results and Conclusions

Integrated results of the projects and correlation with other investigations are presented by major item. These are followed by abstracted results of the individual projects.

Limestone Type: All studies have noted marked differences in reactivity between limestone types. In-house, fixed-bed experiments showed a five-fold range in SO_2 capacity: marl and chalk were the best. Differential reactor results were widely spread: marl was the best[5].[*] Pilot plant data also showed the pronounced effect of limestone type: aragonite was the best at Peabody Coal,[4] and marl was the best at Babcock & Wilcox.[3] Initially these results may not appear to agree; however, it is significant to note that the best performing limestone types were fine grained and generally high in calcium carbonate, as opposed to dolomitic materials. Since calcitic stones (marl and chalk) and aragonite are highly reactive, it appears that both calcium carbonate crystal structures can be used as long as the crystallites (or grains) are small.

Other investigators have compared limestones (i.e., calcites) and dolomites. Goldschmidt[10] and Brocke[12] showed that calcitic additives were more effective than dolomitic additives. A good detailed examination of the effect of limestone type is given by Borgwardt and Harvey.[6]

Chemical Form of the Additive: Many different forms of carbonate rocks have been tried in tests ranging from laboratory to demonstration scale. Most investigators have compared hydrated lime, calcined limestone and uncalcined limestone although dolomitic lime, half calcined dolomite, hydrated dolomitic lime and others have been used on occasion. In general, the ranking of reactivity is hydrated lime > limestone (uncalcined) > lime.[3,7,9] However, the optimum temperatures of injection for different forms of the additive may span 752°F and a comparison at a given temperature is misleading. Zentgraf[7] reports that limestone injected at its optimum temperature (2732°F) is slightly more effective than hydrated lime at its optimum temperature (2102°F). Even in tests where the hydrate is consistently better, the difference is insufficient to warrant the extra cost of the hydrate versus the uncalcined limestone. Tests with dolomitic counterparts of the limestone (i.e. calcite) chemical forms also show the hydrate to be the most reactive but still less reactive than the hydrated lime.[10]

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[*] Superscripts refer to references on pages I-35.

Particle Size: Except in certain cases, all studies noted some increase in reactivity with decreasing particle size. It appears that the effect of particle size is not the same for all stones but is determined primarily by the pore size. Small pores lead to the highest sensitivity between calcine reactivity and particle size. Calcines with very large pores may show no dependence of reactivity on particle size. In differential reactor experiments not much improvement was noted below 100 μ.

At Babcock & Wilcox, particle size was related to specific surface area by the Lea-Nurse technique (air permeability). Depending on the grindability, minus 60 mesh (approximately 250 μ) produces 2000-6000 cm^2/gram in area. The maximum reactivity was recorded when the surface area reached 2000 cm^2/gm or more. Analyses of reacted fly ash showed that particles between 2 and 6μ contained 8 to 12 percent sulfur (as SO_3), and particles greater than 30μ had less than 4 percent sulfur.

These results are generally supported by Battelle[6] and Zentgraf[7] who reported that above 50 and 60μ respectively, the particle size was inversely porportional to the SO_2 reactivity while below these values particle size had no effect. In addition, Ishihara[8] reported that for particles below 10μ the initial reaction rate increased as the particle size decreased and Tanaka[9] reported that for the 3 sizes he studied (all greater than 74μ) a decrease in particle size gave an increase in removal. Zentgraf[7] also reported that as the particle size increases the pore size decreases.

Calcination Temperature: All experiments showed that higher calcination temperatures give rise to loss of reactivity known as dead burning. Both in-house and TVA studies showed that higher temperatures lead to growth of crystallites with a corresponding loss of surface area and pore volume which accounts for the loss of reactivity. In-house, Peabody Coal, and Babcock & Wilcox data show that injection of limestone with the fuel or near the flame gives a dead burned stone with little SO_2 removal efficiency. This conclusion is supported by reports of Goldschmidt[10] and Ishihara.[11] Optimum injection temperatures have been reported to be 2500-2700°F[3], 2000-2450°F[4], 2732°F[7], and 1652-2192°F[8] depending on the system tested. The time-temperature profile is actually the controlling factor.

Catalysts: In-house fixed-bed studies showed no evidence of the limestone-SO_2 reaction being catalyzed by minor constituents in limestone. Both ISGS and TVA showed an improvement in reactivity with sodium content in the stone but no general conclusions could be drawn. At Babcock & Wilcox, vanadium decreased the additive effectiveness but iron oxide improved it slightly. It was concluded that the improvement was due to higher surface areas, not the iron oxide. This is not in agreement with Ishihara[8] who found limestone containing over 1 percent Fe_2O_3 were 50 percent more effective than those with less than 0.5 percent during oil-fired pilot plant experiments. However, SO_2 removals were not increased by addition of ferric oxide powder or yellow ochre to the limestone.

IV. Abstracted Results of Individual Projects

Illinois State Geological Survey[1]—Detailed petrographic, mineralogical, and chemical analysis of 26 carbonate rocks were made and compared with the capacity (3-1/2 hour reaction period) and differential reactivity (120 second reaction period) of calcined specimens for sorption of SO_2. A wide range of petrographic and SO_2 sorptive properties were revealed.

Three petrographic and chemical properties appear to be useful indexes of the SO_2 sorption capacity: the pore volume, the grain size, and the sodium oxide content of the rocks. The larger the pore volume, the greater was the sorption capacity of the rock. Pores with a maximum chord length between 2 and 16μ appear to have the most influence on this behavior. In general, the finer the grain size of the rock, the higher was the sorption capacity, although certain samples showed an opposite correlation owing to the effect of intercrystalline pores in the crinoidal fossil fragments abundant in some of the samples. Of the 15 chemical elements analyzed, only sodium showed a correlation trend with the SO_2 test data. The sodium present in the samples increased with increasing sorption capacity.

The reaction products of the samples calcined at 1796° F for 2 hours and exposed to sulfur oxides in laboratory tests are solid grains of anhydrite ($CaSO_4$). Electron microscopy shows two types of behavior: the calcines of the Iceland spar calcite absorbed sulfur on the outer surface of its particles, whereas in calcines of a porous limestone, absorption took place throughout the particles. Sulfation occurred on the outer surfaces of particles by multiple nucleation of anhydrite crystallites, which enlarged until they abutted each other to produce a tightly interlocking texture of subrounded grains.

The relatively high SO_2 reactivity observed for chalks, calcareous marls, and oolitic aragonite sand samples is believed due mainly to the high pore volume and fine grain size of these carbonate rocks. Geologically, high pore volume is indicated by the relatively unconsolidated nature of these rock materials.

Tennessee Valley Authority[2]—The reactivities of 35 stones were measured and correlated with mineralogical and crystallographic properties.

Calcination of the limestone proceeds from the outside surface toward the center of each particle. The rate of calcination is affected by the reaction temperature, the particle size of the stone, the crystallite size of the carbonate mineral in the stone, the relative amounts of magnesium and calcium in the stone, and the partial pressures of CO_2 and SO_2 in the furnace atmosphere. The reaction of CaO with SO_2 and O_2 at 1682° F is first order with respect to the partial pressure of SO_2 in the range 1 to 8.4 percent by volume, zero order with respect to the partial pressure of O_2 in the range 1 to 10 percent by volume, and zero order with respect to the loading of product until the layer of $CaSO_4$ completely shields the available reaction surface. Below 1182° F, the formation of sulfite predominates over that of sulfate; the oxidation of sulfite to sulfate begins at about 1332° F, a temperature range in which the sulfite also begins to decompose and disproportionate. Disproportionation of sulfite at 1612° F is prevented by the presence of oxygen or CO_2, either of which promotes the formation of sulfate. The first-order specific rate constants for the decomposition of $CaSO_3$ and $CaSO_4$ and the loss of reactivity (dead burning) of a high calcitic (Colbert) limestone were expressed in Arrhenius form.

Water vapor affects the rate of reaction of SO_2 with MgO but not with CaO; the reaction with MgO is too slow to be important under injection conditions. The direct substitution of SO_2 for CO_2 in the limestone also is too slow to be significant under furnace injection conditions. The sulfation reaction occurs simultaneously with the calcination reaction when the rate of the calcination reaction is low; sulfation is more rapid, however, when there is a relatively large surface of unreacted CaO. The products of the sulfation reaction retard the calcination reaction when the two reactions occur simultaneously.

The physical properties of a calcine and its reactivity with SO_2 are influenced markedly by the texture of the parent limestone from which the calcine is formed. An Iceland spar, of mean crystallite size 7125° A., calcined slowly below 1742° F because of its high thermal stability, and yielded a calcine with small pores and small crystallites of CaO. A very pure calcitic limestone, of mean crystallite size 3875° A, yielded larger crystallites of CaO than did the Iceland spar under the same conditions, but the pore volume was larger and more favorably distributed between different sized pores for reaction with SO_2. Between 1832° F and 2012° F the calcines of both materials showed a minimum in pore volume, which was interpreted as the end of sintering and the beginning of recrystallization of the CaO. During sintering, small pores coalesce into larger pores with small changes in the crystallite size of the oxide; during recrystallization the crystallites grow into massive single crystals of CaO at rates proportional to the crystallite size of the original carbonate. The Iceland spar was less reactive with SO_2 than was the calcitic limestone under all the experimental conditions tested because of its slower calcination, its unfavorable pore-size distribution and pore volume, and its more rapid recrystallization. Electron microscope photographs of cleaved sulfated particles of these stones clearly showed the reaction zone between oxide and sulfate and the growth of the crystallites of sulfate at the outer surface.

The calcination, isothermal sulfation, and polythermal calcination-sulfation of 35 limestones were studied and the distinguishing characteristics of each reaction were correlated with the chemical and mineralogical properties of the stones. Six measures of the capacity and rate of reaction with SO_2 were correlated with the chemical and mineralogical properties of the stones, as well as the reaction parameters. Multiple correlations of the capacity and rate parameters with the properties of the stones yielded equations from which the reactivity of a stone could be predicted from its chemical and mineralogical characteristics. The equations were tested with five stones considered for use in the Shawnee full-scale tests, using the reaction rate data at five temperatures obtained by Battelle in the dispersed-phase reactor. The prediction of the polythermal capacity for absorption of SO_2 from the chemical and mineralogical properties of the stones correlated well with the Battelle reaction rates at temperatures below 1724° F, but not at higher temperatures. No other predicted reactivity measure correlated significantly with the Battelle rate at any temperature.

Although the data obtained at the temperatures accessible in this experimental study (maximum of 1742°F) do not extrapolate well to the higher temperatures that are encountered in actual power plant combustion chambers, the properties of stones that were shown to be desirable at low temperatures probably will be advantageous at the furnace temperatures also. Perhaps the major difference to be expected between the results obtained at low temperature and those anticipated at high temperatures is the marked increased in the rate and extent of dead burning at the high temperatures, as indicated by the results of the X-ray examinations. The data indicate no way of avoiding the detrimental effect of rapid dead burning at temperatures above about 1922°F. They indicate that stones that contain the smallest amounts of impurity minerals and whose rhombic carbonates are primarily calcitic and are present as the smallest crystallites will be most effective for injection into the combustion chamber. Increasing the sodium content of the stone increases its reactivity; however, if iron is present, it should be in the form of limonite or goethite rather than in the lattice of the stone.

Babcock & Wilcox[3]—Using a small pulverized coal pilot plant, 415 tests were run with 129 different additives. The variables studied relative to additive reactivity included temperature at the point of injection, residence time of the additive in the reactive zone, additive surface area, chemical form of the additive (e.g., carbonate, oxide, or hydrate) and catalyst content.

In general, raw limestones and dolomites were most effective when injected into the pilot plant at points corresponding to mid- and upper-furnace regions of full-scale units. This behavior appeared in part to be an effect of gas temperature, but particle residence time was probably the most important factor. Feeding the raw additives with coal or upstream of the combustion zone resulted in very poor performance, indicating that dead burning took place under these conditions.

Increasing additive specific surface area to about 2000 cm^2/g, or slightly higher, improved additive performance to a maximum. Larger surface area gave no further improvement, and in some cases the amount of SO_2 removal was actually decreased, probably due to agglomeration of very fine particles.

Hydrated stones were slightly more effective than their parent raw material, particularly at lower (approximately 1900°F) injection temperatures, but not to the extent that the cost of additive processing would be justified. Precalcining the stones in most cases decreased effectiveness of the additives.

Iron oxide (as Fe_2O_3 and Fe_3O_4) was found to improve additive effectiveness slightly while vanadium (as V_2O_5) actually decreased it. It was concluded that improved effectiveness resulted from higher surface areas, not the iron oxide.

Marl, a kind of limestone, was the most effective type of additive tested under most conditions.

Peabody Coal Company[4]—Tests were conducted in a pilot size chain-grate stoker with an aragonite, a calcite, two types of dolomite, and a chalk. "Red mud," the dried tailings from the manufacture of alumina from bauxite was also tested. Variables related to additive reactivity included temperature at the point of injection and particle size. Calcination and calcium oxide utilization were determined.

Sulfur dioxide removal ranged from 6 to 65 percent depending upon operating conditions. A comparison of sorbents, compared on a per-unit-weight-of-raw-stone basis, shows that the calcites and aragonite remove more SO_2 than do dolomites. Sorbent 1683, an aragonite, was the most effective material tested when injected into the gas stream. However, it was relatively ineffective when mixed with the coal prior to combustion.

The particle size study was not as definitive as desired due to overlapping particle sizes between injected screen cuts. A step-wise regression analysis of 59 runs, with samples 1337 and 1684 (dolomite), 1683 (aragonite), and 1359 (calcite) combined, indicated that reducing the sorbent particle size leads to higher SO_2 removal rates.

Each sorbent, except red mud, was injected at temperatures from 1800° F to 2450° F. Computer results on all test data combined did not indicate a significant correlation between SO_2 removal and injection temperature. However, graphical analysis did indicate that temperature was a significant parameter for some of the individual samples.

The degree of sorbent calcination varied directly with temperature and ranged from 50 to 60 percent at 1800° F to more than 90 percent at 2450° F. Above 2000° F, particle size did not appear to significantly affect the degree of calcination.

Calcium oxide utilization varied from 6.30 percent (for particle sizes greater than 100 mesh) to 59.50 percent (for 200 mesh sizes). Aragonite, Sample 1683, and dolomite Sample 1684, demonstrated the greatest utilization.

Red mud, when injected into the gas stream at 1200° F to 1300° F and 2000° F was relatively ineffective in removing SO_2.

In-House EPA[5]—Eighty-six carbonate rock samples were tested in a fixed-bed reactor to determine their capacity to react with flue gas containing SO_2. Although most of the work was performed with the carbonate and the oxide at standard test conditions, supplementary tests were made on hydrates, oxides, and carbonates over a wide range of reaction temperatures and calcination conditions. Differences between the samples were related only slightly to chemical composition; porosity, as measured by mercury pore volume best explained variations in capacities of the samples. Chalks and oolitic samples were the most efficient absorbents; magnesite and Iceland spar the least efficient of the stones tested.

The SO_2 reaction kinetics of calcines prepared from 11 rock types representing a broad spectrum of limestones and dolomites, which were examined by ISGS, were determined at 1800° F. Stones of various geological types yield calcines of distinctly different physical structures that show correspondingly large differences in both rate of reaction and capacity for SO_2 sorption. Pore size and particle size together determine the extent to which the interior of individual particles react. Particles smaller than 0.01 cm (100 μ) with pores larger than 0.1μ react throughout their internal pore structure at a rate directly proportional to the B. E. T. surface. The rate decays exponentially as sulfation proceeds until the pores are filled with reaction product. The ultimate capacity of small particles is determined by the pore volume available for product accumulation, generally equivalent to about 50 percent conversion of the CaO in limestones. Variations in effectiveness of carbonate rocks for flue gas desulfurization are explained by the physical properties of their calcines, which are related to the crystal structure of the original rock. The high reaction rates achieved in the limestone injection process apparently result from the large surface area existing for short periods immediately following the shock dissociation of $CaCO_3$.

The relative ranking of calcines with respect to isothermal rate of reaction with SO_2 at 1796°F is: marl > high purity limestone > Iceland spar > aragonite > marble. Magnesite reacts only slowly with SO_2 at any temperature between 1004 and 1796°F.

The relative ranking of limestones with respect fo fixed bed capacity at 1796°F with -18 +20 mesh particles (approximately 840-1000 μ) is: marl chalk > oolite > dolomite > calcite > marble> magnesite> Iceland spar.

The rate of reaction increases with decreasing pore size until a critical pore diameter of about 0.1u is reached. Presumably pores smaller than 0.1μ are rapidly blocked by reaction products. Maximum rate results when B. E. T. surface area is in the region of 3.5 M^2/g (corresponding to pore diameters of 0.2 - 0.3μ) under isothermal reaction conditions.

The total SO_2-sorption capacity increases with increasing pore size. Furthermore, the capacity of limestones is correlated to the area of pores greater than 0.3μ but not to B. E.T. surface area.

Both rate and capacity of SO_2 sorption are highly dependent upon particle size. The effect of particle size is not the same for all stones, but is determined by the size of the pores.

Small pores lead to the highest sensitivity between the reactivity of calcines and particle size. Calcines with very large pores may show no dependence of reactivity upon particle size.

Loss of reactivity because of high calcination temperatures (dead burning) is attributed to growth of CaO crystals and the subsequent loss of surface area and pore volume. During sintering and CO_2 evolution, small pores coalesce into larger pores with small changes in crystallite size of the oxide. At excessive temperatures recrystallation occurs and the crystallites grow into massive single crystals at rates proportional to the crystallite size of the original carbonate. Since loss of surface area and loss of pore volume are similar functions of increasing calcination temperature, both reaction rate and capacity of dead-burned stones are lost proportionally.

Four reactivity tests—flue gas absorption, SO_2 absorption, CO_2 absorption, and hydration weight gain were found to be suitable as dead-burning tests for samples of limited size diluted with fly ash. The last three are considered sufficiently uncomplicated to be used as field tests.

V. Recommendations on Limestone Properties for Application to the Dry Limestone Injection Process

a. A fine-grained (e.g., having small crystallites) high calcium carbonate stone should be used. While many common limestones are of this type, marl, aragonite, and chalk are almost always fine grained. Many deposits of chalk and marl are sufficiently pure for the injection process and most deposits of aragonite are very pure.

b. Injection of uncalcined limestone is indicated except where only injection at low temperature (< 1800° F) is possible. In this case lime hydrate should be used.

c. The additive should be finely ground. While improvement does not appear to be significant below 100μ, a directional improvement has been shown. A particle size of 90 percent minus 300 mesh (approximately 50μ) is preferable.

d. The additive should not be injected with the fuel or near the flame. The optimum injection point is a function of the system to be controlled but should be approximately 2000-2200° F. The optimum injection temperature may be higher in boilers where the residence time in the hottest zone is very short. In any case the injection point should be located so as to insure complete calcination without dead burning.

e. The hydration weight gain test for dead burning is recommended since it is independent of the degree of sulfation.

Section B

Limestone Availability in the United States[1]

I. Introduction and Objectives

A great deal of emphasis is being placed on the development of processes which remove sulfur oxides from the stack gases of plants which burn coal or oil as a primary fuel. Several of these processes are based on the use of limestone or dolomite as the sorbent for the sulfur oxides. The use of these materials to control sulfur emissions is contingent upon several factors. Among these, the proximity of adequate carbonate rock deposits to potential users and the relationship of carbonate rock production to possible demand, appear to be most important in establishing the relative merits of any carbonate rock-based process. The objective here was the determination of the availability and costs of limestone and similar materials throughout the contiguous United States to provide a basis for determining the feasibility and economics of limestone-based SO_2 removal processes for typical plant sites.

II. Approach

Search of publications and communications with Federal and state government agencies, trade associations, and various crushed stone or limestone producers were the sources of the data presented. The data was gathered on a national, regional and state-wide basis. Since the objective is primarily concerned with limestone availability as it relates to potential consumption by fossil fueled power plants, the regions were chosen to coincide with those defined by the National Coal Association. Materials covered include limestone, dolomite, chalk, marble, marl and shell. Location of deposits, production rates, f. o. b. quarry costs, transportation methods and costs, expected cost increases, uses, chemical composition and physical properties were covered. Summary results most germane to this report follow. Additional details in these and other areas may be found in the references provided.

III. Results

Potential Demand - Power Plants

Most of the power capacity from fossil fuel-fired power plants in the United States occurs in the eastern half of the country. Figure 1 shows the location of the major (≥200 MW) power plants in the United States which burn either coal or oil as the primary fuel. Included are a few plants which, although not yet constructed, are being designed exclusively for either coal or oil and are scheduled to be on stream by 1975. Of the 275 plants shown, 84 percent are coal-fired. The oil-fired plants are all located along the eastern coast, with most of these in the northeast. About 90 percent of all power plants shown are located east of the Mississippi River, with locally high concentrations in the northeastern quarter of the country, particularly in many of the major metropolitan areas.

1, Adapted from references 13 and 14.

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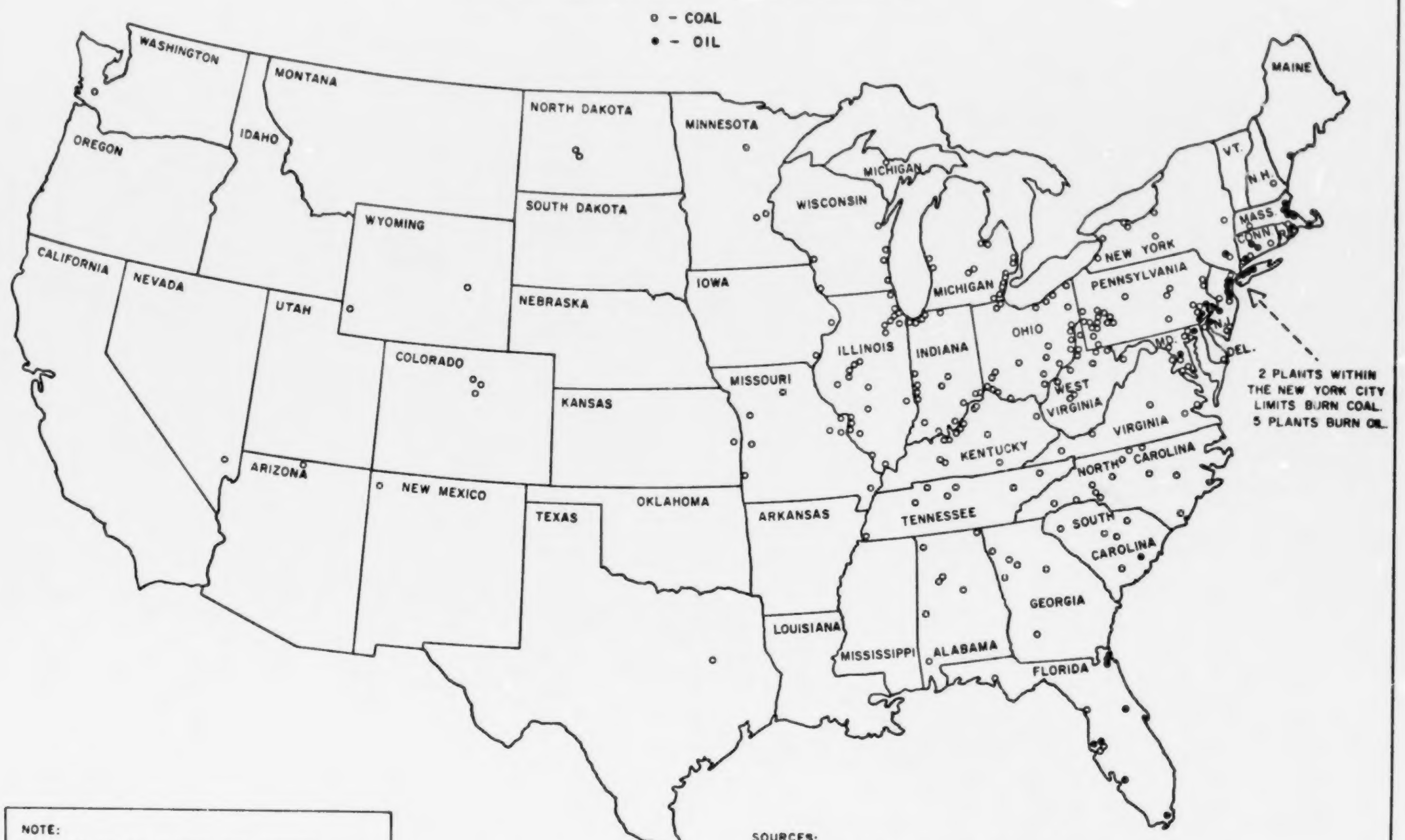
FIGURE 1

MAJOR THERMAL POWER PLANTS IN THE UNITED STATES BURNING COAL OR OIL AS THE PRIMARY FUEL


o - COAL
● - OIL
WASHINGTON
MONTANA
OREGON
IDAHO
NORTH DAKOTA
MINNESOTA
SOUTH DAKOTA
WYOMING
WISCONSIN
MICHIGAN
CALIFORNIA
NEVADA
UTAH
IOWA
NEBRASKA
MICHIGAN
NEW YORK
PENNSYLVANIA
ILLINOIS
INDIANA
OHIO
COLORADO
MISSOURI
KANSAS
WEST VIRGINIA
VIRGINIA
KENTUCKY
ARIZONA
NEW MEXICO
OKLAHOMA
NORTH CAROLINA
TEXAS
ARKANSAS
TENNESSEE
SOUTH CAROLINA
GEORGIA
LOUISIANA
MISSISSIPPI
ALABAMA
FLORIDA
MAINE
VT.
N.H.
MASS.
CONN.
R.I.
N.J.
MD.
DEL.

2 PLANTS WITHIN THE NEW YORK CITY LIMITS BURN COAL. 5 PLANTS BURN OIL.

NOTE:
MAJOR POWER PLANTS ARE DEFINED AS THOSE HAVING INSTALLED GENERATING CAPACITIES OF 200 MEGAWATTS OR MORE.

SOURCES:
1. *Principal Electric Facilities*, Federal Power Commission, (1970). (Series of seven maps)
2. *Steam-Electric Plant Factors/1970 Edition*, National Coal Association, Washington, D.C., (November 1970).

Based on 1969 fuel consumption statistics, an estimated 20 million tons of sulfur oxides were emitted by power plants in the United States. Assuming 1.25 stoichiometry, more than 40 million tons of limestone would have been required to remove these oxides from the stack gases. This potential limestone demand, which assumes that all power plants use a limestone-based process for sulfur removal, has been broken down by region, with the regions being defined as follows:

Region	States Included
New England	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont
Middle Atlantic	New Jersey, New York, Pennsylvania
East North Central	Illinois, Indiana, Michigan, Ohio, Wisconsin
West North Central	Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, South Dakota
South Atlantic	Delaware, Florida, Georgia, Maryland (including Washington, DC), North Carolina, South Carolina, Virginia, West Virginia
East South Central	Alabama, Kentucky, Mississippi, Tennessee
West South Central	Arkansas, Louisiana, Oklahoma, Texas
Mountain	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
Pacific	California, Oregon, Washington

Table 1 itemizes potential demand by region. The East North Central region far outranks any other region in potential limestone requirements with over one-third of the total. With the exception of New England, all regions in the eastern half of the country had potentially large demands for limestone.

Table 1

Potential Limestone Demand by Power Plants in the United States

Region	Limestone (10^3 Tons)	% of Total
New England	1,369	3.4
Middle Atlantic	6,583	16.2
East North Central	14,307	35.1
West North Central	2,738	6.7
South Atlantic	8,471	20.8
East South Central	5,645	13.9
West South Central	5	-
Mountain	1,351	3.3
Pacific	266	0.6
Total	40,735	100.0

Carbonate Rock Reserves

Deposits of carbonate rocks, including limestone, dolomite, shell, marble, and marl, occur in some form in every state. Total reserves have never been estimated, but are known to be enormous.

Figure 2 shows the distribution of surface carbonate rocks in the United States and includes limestone, dolomite, and marble. The map shows that surface deposits of carbonate rocks occur throughout the nation but are particularly in evidence in the eastern half of the country. A band of deposits beginning in Vermont extends southward along the Appalachian Mountains into central Alabama. Extensive deposits are found in the state surrounding the Great Lakes, reaching southward into northern Alabama. Large areas of Minnesota, Iowa, and Missouri are covered with carbonate rocks and broad outcrops occur in Kansas, Oklahoma, Arkansas, and Texas.

Particularly in the central lowlands, carbonate rock deposits frequently occur as thick, horizontal formations covering large areas. In general, the deposits found in western states are different. They commonly occur as steeply dipping or vertical beds of small areal extent. However, notable exceptions to this are found, particularly in Colorado, Arizona, and New Mexico where large outcrops occur.

Limestone occurrences, including chalk but excluding dolomite, are shown in Figure 3. The map is similar to Figure 2 and shows that although limestone is found throughout the

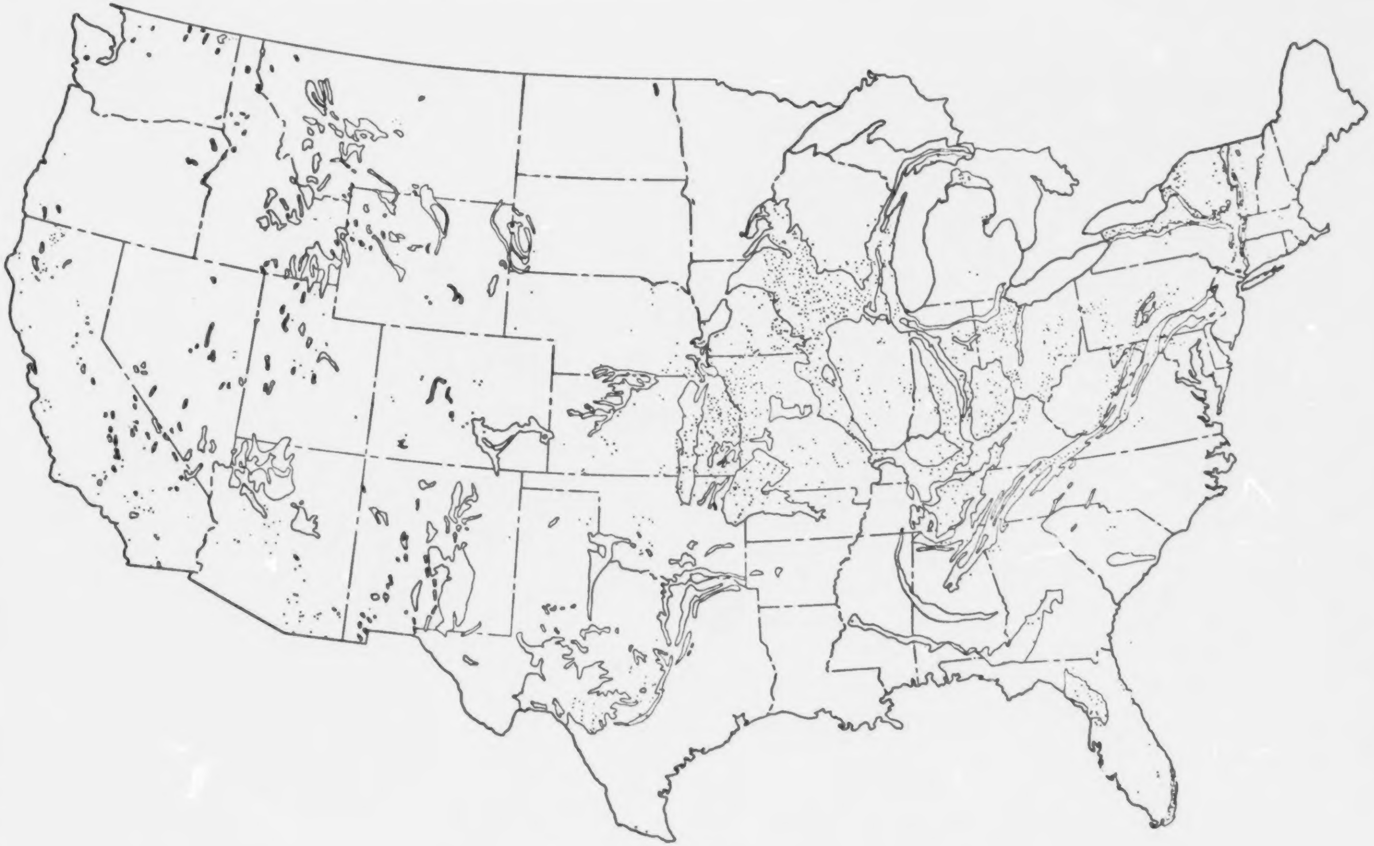


FIGURE 2

CARBONATE ROCK DEPOSITS IN THE UNITED STATES

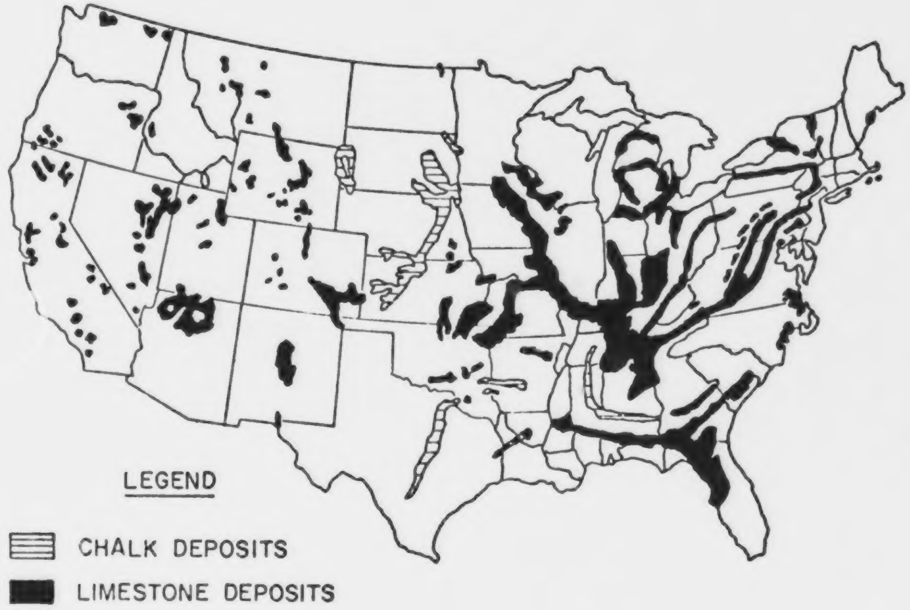

LEGEND
▤ CHALK DEPOSITS
■ LIMESTONE DEPOSITS

FIGURE 3

DISTRIBUTION OF CHALK AND LIMESTONE DEPOSITS IN THE UNITED STATES

(REPRINTED FROM U.S. BUREAU OF MINES BULLETIN NO. 395) country, the more numerous and extensive deposits occur in the eastern half of the nation. In the western states, the deposits tend to be discontinuous and relatively small in areal extent.

The formations shown in Figure 3 include limestones of different degrees of purity. Estimates have been made that only about 2 percent of the known reserves of commercially usable limestone is chemical grade (> 95 percent carbonate content), and that the bulk of these reserves will be exhausted in 40-50 years. Much of this high purity limestone occurs in the area extending from the Great Lakes southward to Alabama.

Chalk deposits are shown in several of the central states and in a curving belt through Alabama and Mississippi. In general, they are not high purity limestones, but locally they may contain over 95 percent calcium carbonate.

Figure 4 shows the location of high grade (> 25 percent magnesium carbonate) dolomite quarries. Although originally drawn in 1941, it is a useful guide to the important occurrences of dolomite. As with limestone, the largest deposits are located in the eastern half of the country. Two major areas are noted. First a belt of dolomite extends from Vermont to central Alabama along the Appalachian Mountains. This coincides quite well with a similar band of limestone previously noted. Second, large formations of dolomite occur in the states encircling the Great Lakes. These deposits coincide with or adjoin large limestone deposits in the region.

The most significant deposits of marble are found along virtually the entire length of the Appalachian Mountains in the east, and as scattered occurrences in the Rocky Mountains in the west. Although eastern marbles are predominantly calcitic (high calcium), dolomitic types also occur. Both types are found in the west.

Shell limestone occurs primarily in Gulf Coastal waters, but it also is found in bay waters along both the east and west coasts. It is usually a very pure type of calcium carbonate.

Marl deposits exist in several areas, notably around the Great Lakes, and along the southeastern coastal plain. This soft, relatively impure form of calcium carbonate varies considerably in character, that of the Great Lakes area being precipitated calcium carbonate, while that of the coastal plain is an impure shell deposit. Limited occurrences in other regions are generally impure chalks or soft limestones.

Mining and Production

Carbonate stones are recovered by several methods, including underground mining and dredging but quarrying is employed most commonly. After removal of overburden and primary blasting of the stone, various crushing, grinding, sizing, and cleaning operations are performed to produce a range of marketable products. A large, modern quarry is an expensive, complex, and highly mechanized unit.

Over 4,700 quarries, producing 861 million tons of crushed stone of all types, were in operation in the United States in 1969. Since production of crushed carbonate rocks totaled 652 million tons, it can be assumed that, roughly, over 3,500 of these quarries

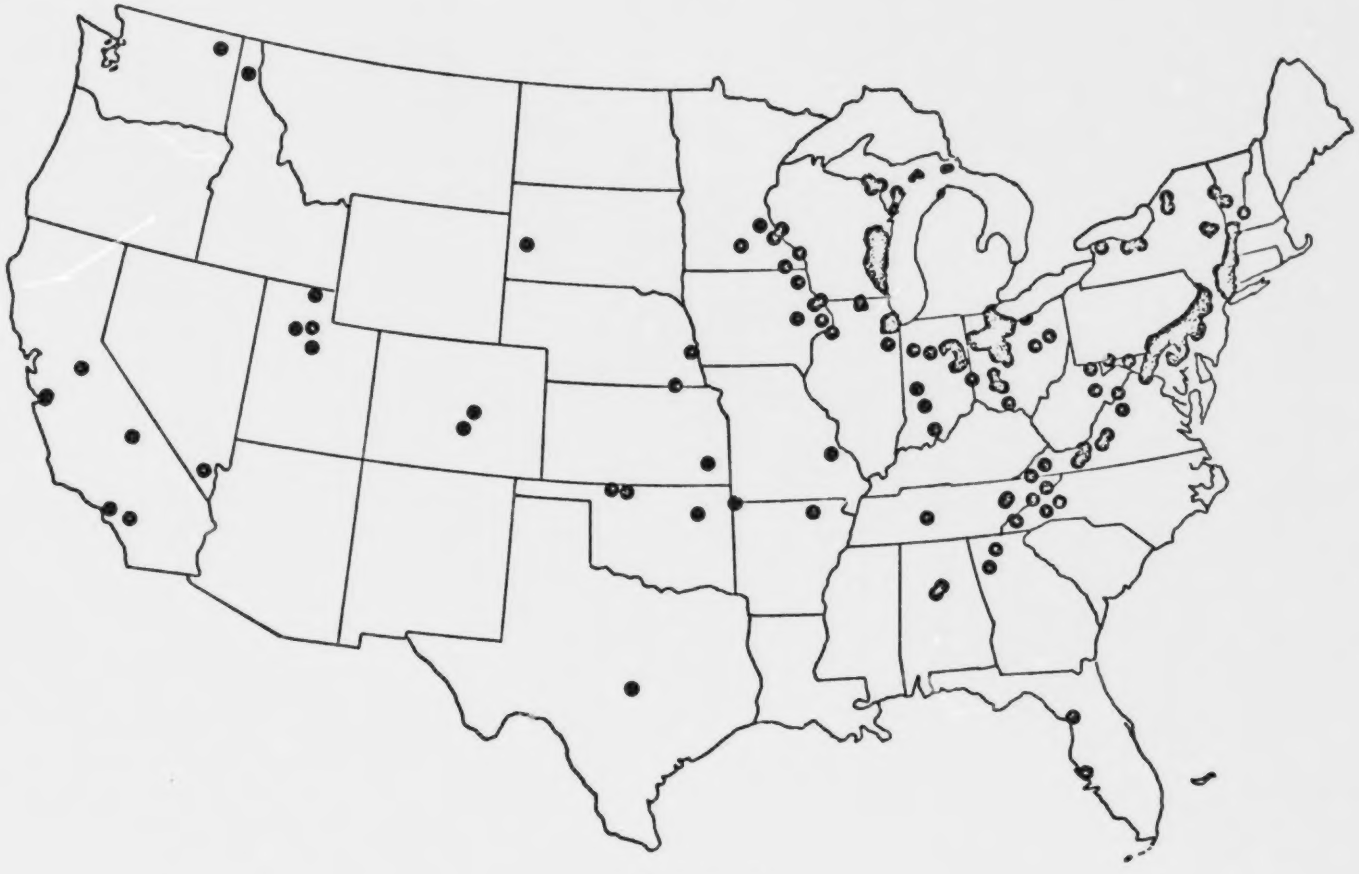


FIGURE 4

LOCATION OF HIGH-GRADE DOLOMITE QUARRIES IN THE UNITED STATES

(REPRINTED FROM U.S. BUREAU OF MINES INFORMATION CIRCULAR NO. 7192) produced limestone, dolomite, and related stones. More than one-third of all quarries had annual production rates of less than 25,000 tons. The large operations (over 900,000 tons/year) produced one-third of the total crushed stone, although they represented less than 4 percent of the total number of quarries.

Crushed carbonate rock production in the United States in 1969 was distributed as follows:

	10^6 Tons
Limestone	559.0
Dolomite	68.0
Shell	20.0
Calcareous Marl	2.5
Marble	2.3
Total	652

No production of any type was reported in three states, viz., Delaware, New Hampshire, and North Dakota. These states, plus Louisiana, were the only states which did not produce any limestone. Dolomite was produced in twenty-four states, chiefly in the north-eastern quarter of the country.

Production of limestone and dolomite, by region, was a follows:

	10^6 Tons
New England	2.4
Middle Atlantic	90.9
East North Central	185.6
West North Central	92.5
South Atlantic	87.5
East South Central	81.3
West South Central	58.3
Mountain	10.7
Pacific	18.8
Total	628

Nationwide, Pennsylvania and Illinois were the leading producers of limestone and dolomite, respectively. Within most regions, production rates of individual states varied from near zero to tens of millions of tons. The New England and Mountain regions, however, had fairly uniform and low outputs. The East North Central region was also an exception, with all states reporting large quantities of limestone and dolomite, ranging from 16 to 55 million tons.

Shell was dredged from bay waters along all three coasts. However, 83 percent came from Texas and Louisiana, with the latter being the leading producer. Small quantities of marl were produced in Indiana, Michigan, Minnesota, Mississippi, Nevada, South Carolina, Texas, and Virginia. Eighteen states, principally in eastern and western mountainous regions quarried marble, with Alabama recording the highest production at 632,000 tons.

IV. Supply/Demand Relationship of Carbonate Rocks for Pollution Control

Proximity of Carbonate Rock Deposits to Power Plants

Comparison of Figures 1-4 indicates that the major deposits of carbonate rocks largely coincide in location with the power plants. This is particularly true in the East North Central region where huge reserves of stone occur. Both high calcium limestone and high grade dolomite abound and many deposits are found near the major power generation centers throughout the region.

The New England region is not as fortunate. While the power plants are located primarily in coastal areas, the rock deposits occur in the mountainous western sections. Most of the deposits are highly crystalline stone or marble and many are dolomitic. The suitability of these materials would have to be determined before including them as a possible source.

Availability of stone should not be a problem for power plants in the Middle Atlantic region. All types of stone occur and nearby deposits can be found. Plants in western and eastern Pennsylvania, particularly, are fortunate in that large reserves of high grade stones are present.

In the South Atlantic region, most plants are located near an adequate source of stone, particularly if the crystalline limestones and dolomites of the mountainous areas prove suitable. Several coastal plants could use shell or coral limestone, or marl. However, for some inland power plants in North Carolina, for example, no nearby deposits exist.

Large quantities of high calcium limestone occur throughout the East South Central region and power plants should experience no difficulty in obtaining adequate supplies. Many plants located in Alabama and Tennessee also could obtain dolomite quite easily.

The less abundant and more widely scattered carbonate resources of the western states are of minor importance, since there are few coal-fired power plants in this area. With the exception of the two power plants located in North Dakota, which are far removed from any commercially important carbonate deposits, the few plants that do exist are fairly near reserves of high calcium stone.

Potential Demand Relative to Production

As previously mentioned, the potential demand for limestone by coal- and oil-fired power plants in 1969 exceeded 40 million tons. This represents only 7.3 percent of the national limestone production of 559 million tons. Dolomite production, on the other hand, was roughly 60 percent greater than the potential demand. Shell production was only one-half of the demand. The quantities of calcareous marl and crushed marble quarried were relatively insignificant. Obviously, limestone is the only stone produced in sufficient quantities to warrant nationwide consideration as an agent for SO_2 removal. Dolomite and shell, however, are quarried in large enough amounts to make them important materials in some regions. Marl and crushed marble may be useful in certain localities where the other rocks do not exist but their limited occurrence and production do not permit wide-scale use of these materials.

Table 2 shows the relationship of limestone and dolomite production to potential demand, by region and state. The third column of the table is the ratio of total limestone and dolomite production to potential demand, for 1969.

With the exception of New England, the eastern regions of the country all have large relative supplies of limestone and dolomite. There are some exceptions to this among the individual states. New Jersey and Delaware have a potential need which exceeds their production. Adjacent states, however, are large producers of stone and could provide the necessary tonnages. Mississippi and both of the Carolinas have low relative supplies of stone. If they could not otherwise be supplied, marl deposits which occur extensively in all three states could be used. Georgia and West Virginia, with comparatively low relative supplies, could easily obtain needed stone from surrounding states. It is interesting to note that the region with the highest limestone demand, i.e., the East North Central region, also has the highest limestone and dolomite production.

The New England region faces a shortage of limestone and dolomite, with two states producing less stone than potentially required. The marble resources of the region could improve the situation somewhat, but power plants would have to rely on shipments of stone from nearby states such as New York, or, perhaps, on imports.

Most states in other regions of the country have ample production. North Dakota, with no production, is an outstanding exception to this, however. A few other states have low relative supplies of stone, but either the demand is quite small, or the production could easily be expanded to meet the need.

Costs

F.O.B. Quarry Costs

The average unit value, or net selling price at the quarry, for all crushed carbonate stones produced in the United States in 1969 was $1.49/ton and varied by type of stone as follows:

Limestone	$1.45/ton
Dolomite	$1.55/ton
Shell	$1.42/ton
Marl	$1.01/ton
Marble	$9.69/ton

The high unit value of marble reflects its primary use as a decorative material.

Unit value also varies with end use. Stone used for all construction purposes averaged $1.44/ton while stone used in applications requiring a high purity material had an

Table 2

Availability of Limestone and Dolomite for Pollution Control (1969)

Region and State	Production (10^3 Tons)	Potential Demand (10^3 Tons)	Ratio
New England			
Connecticut	275	487	0.56
Maine	800	61	13.1
Massachusetts	750	636	1.18
New Hampshire	-	141	0
Rhode Island	< 100	39	<2.56
Vermont	525	5	105
Totals	2,400	1,369	1.75
Middle Atlantic			
New Jersey	800	935	0.86
New York	33,457	2,132	15.7
Pennsylvania	56,667	3,516	16.1
Totals	90,900	6,583	13.8
South Atlantic			
Delaware	-	177	0
Florida	40,729	1,009	40.4
Georgia	4,334	931	4.66
Maryland	9,804	1,010	9.71
North Carolina	4,500	2,003	2.25
South Carolina	1,900	459	4.1[illegible]
Virginia	17,829	1,088	16.4
West Virginia	8,405	1,794	4.69
Totals	87,500	8,471	10.3
East South Central			
Alabama	17,752	1,931	9.19
Kentucky	30,158	1,785	16.9
Mississippi	300	71	4.23
Tennessee	33,109	1,858	17.8
Totals	81,300	5,645	14.4
East North Central			
Illinois	54,844	3,665	15.0
Indiana	25,157	2,786	9.03
Michigan	39,066	2,511	15.6
Ohio	50,595	4,181	12.1
Wisconsin	15,937	1,164	13.7
Totals	185,600	14,307	13.0
West North Central			
Iowa	26,200	453	57.8
Kansas	15,334	42	365
Minnesota	4,127	648	6.37
Missouri	41,200	1,093	37.7
Nebraska	4,663	110	42.4
North Dakota	-	357	0
South Dakota	989	35	28.3
Totals	92,500	2,738	33.8

Table 2 (continued)

Region and State	Production (10^3 Tons)	Potential Demand (10^3 Tons)	Ratio
West South Central			
Arkansas	5,676	4	1419
Louisiana	-	<1	0
Oklahoma	16,300	<1	Large
Texas	36,300	<1	Large
Totals	58,300	<7	Large
Mountain			
Arizona	2,339	50	46.8
Colorado	1,650	358	4.61
Idaho	250	-	∞
Montana	1,442	74	19.5
Nevada	1,000	78	12.8
New Mexico	956	345	2.77
Utah	2,400	67	35.8
Wyoming	649	379	1.71
Totals	10,700	1,351	7.92
Pacific			
California	17,400	266	65.4
Oregon	350	<1	Large
Washington	1,050	<1	Large
Totals	18,800	<268	>70

average value of $1.69/ton. Average prices ranged from $0.69/ton for fill to $6.00/ton for exposed aggregate (decorative stone). Stone for most applications, however, averaged under $2.00/ton. The variation in price depends not only on supply and demand but also on the chemical and/or physical properties required for the particular application.

Average prices of limestone and dolomite are shown in Table 3, by region and state. Within most states, average prices were $1.00-$2.00/ton, although spot prices ranged from $0.12-$25.00/ton. Several states in the New England and Mountain Regions, in addition to New Jersey, reported average values above $2.00/ton. Rhode Island reported the highest average value: $7.57/ton for limestone. The prices reported in California and Washington were unusual in that average values for limestone were below the national average, while average values for dolomite far exceeded $2.00/ton. Production of the particular stone was limited in all cases where average unit values were high.

With the exception of Virginia, which reported $3.92/ton, average prices of shell were $1.00-$2.00/ton. Unit values for marl were all below $1.15/ton and varied widely in price.

Transportation Costs

Trucks dominated in the transportation of carbonate rocks from quarry to consumer, accounting for almost three-fourths of all stone. Rail and waterway hauls, amounting to one-fifth of the stone shipments, were about equally divided.

Trucks generally are used for shorter hauls of under 50-100 miles while rail is employed for longer distances. Where conditions permit, shipment of stone by barge or boat is preferred since this is usually the cheapest method of transportation.

Typical capacities of the various vehicles used to transport stone are:

Truck	up to 50 tons
Rail Car	60-100 tons
Barge	1200-1400 tons
Boat	up to 29,000 tons

Trucks were a popular mode of transportation in all sections of the nation, while railroads were important in eastern states, particularly in the southeast. Large amounts of stone were moved via inland waters, notably in the Great Lakes area and along the Gulf Intracoastal Waterway. The abundance of highways, railroads, and inland waterways found in the east is not duplicated in western states, thereby limiting the selection of a transportation method in the latter area.

Generally, sufficient trucks, barges, and boats are available to haul stone although in some areas in peak seasons the supply may be limited. In most sections of the country a shortage of rail cars does occur. For a power plant where the limestone demand would be known and deliveries could be scheduled well in advance, the affect of a shortage of vehicles should not be severe.

Table 3

Unit Value of Crushed and Broken Limestone and Dolomite in the United States in 1969, By Region and State

Region and State	Average Unit Value ($/Ton)	
	Limestone	Dolomite
New England		
Connecticut	NR[1]	4.20
Maine	1.32	-[2]
Massachusetts	4.14	5.24
New Hampshire	-	-
Rhode Island	7.57	-
Vermont	1.46	1.53
Middle Atlantic		
New Jersey	2.49	-
New York	1.56	1.97
Pennsylvania	1.46	1.73
East North Central		
Illinois	1.44	1.45
Indiana	1.32	1.28
Michigan	1.02	1.45
Ohio	1.54	1.48
Wisconsin	1.17	1.21
West North Central		
Iowa	1.49	1.72
Kansas	1.40	-
Minnesota	1.32	1.38
Missouri	1.39	1.13
Nebraska	1.87	-
North Dakota	-	-
South Dakota	1.22	-
South Atlantic		
Delaware	-	-
Florida	1.31	-
Georgia	1.50	
Maryland	1.57	-
North Carolina	1.62	-
South Carolina	1.51	-
Virginia	1.52	1.37
West Virginia	1.62	1.62

---

1. "NR" indicates that value was not reported
2. "-" indicates no production

Table 3 (continued)

Region and State	Average Unit Value ($/Ton)	
	Limestone	Dolomite
East South Central		
Alabama	1.17	1.60
Kentucky	1.46	-
Mississippi	1.00	-
Tennessee	1.33	-
West South Central		
Arkasas	1.36	-
Louisiana	-	-
Oklahoma	1.30	NR
Texas	1.35	1.17
Mountain		
Arizona	1.64	-
Colordao	2.04	2.83
Idaho	1.10	-
Montana	1.24	-
Nevada	1.64	1.77
New Mexico	1.51	NR
Utah	2.25	2.66
Wyoming	2.11	-
Pacific		
California	1.07	2.91
Oregon	1.00	-
Washington	1.28	6.00
Total United States	1.45	1.55

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1. 'NR" indicates that value was not reported
2. "-" indicates no production

So many factors influence transportation rates and costs that it becomes very difficult to establish average rates, even within a single area. Most freight rates for crushed stone in the United States fall within the following ranges, in cents per ton-mile:

Truck	5.0-10.0 (@ 10 miles)	→	2.0 - 5.0	(@ 100 miles)
Rail	4.5- 6.0 (@ 10 miles)	→	0.75 - 1.5	(@ 250 miles)
Water	0.9- 1.5 (@ 20 miles)	→	0.25 - 0.50	(@ 500 miles)

Delivered Costs

The delivered price of limestone to a power plant is the sum of the price of the stone at the quarry plus the transportation charges. The delivered price of limestone to 37 selected power plants is estimated in Table 4, based on the assumption that a calcium limestone would be required. Most of the plants are located in the eastern half of the United States where the major coal- and oil-fired power capacity is found. Prices range from $1.95-$13.20/ton. Half of the plants could be supplied at under $4.00/ton, while all but 3 could obtain limestone at under $6.00/ton. The latter 3 plants are located in the west in areas where base prices are higher or limestone deposits are remote. For several eastern seaboard plants, particularly in New England, the availability of low-cost high calcium limestone is contingent upon the acceptability of an imported stone. Domestic sources are either inadequate or too distant to provide a low-cost material.

Carbonate rocks historically have been stable, low-priced commodities. Based on average unit values for the years 1960-1969, projected average base prices for 1975 are as follows:

	1969	1975
Limestone and Dolomite	$1.46/ton	$1.67-1.82/ton
Marl	$1.01/ton	$1.28-1.48/ton

The average value of shell has dropped considerably since 1960. It is unlikely that it will continue to decrease through 1975. More probably, it should parallel limestone and dolomite but not exceed them in value. Average unit values for crushed marble are highly variable, reflecting the sensitivity of price to market conditions.

Transportation rates during the next 5 years should rise about 6 percent/year, on the average. Estimates by type of transportation are as follows:

Truck	4 - 6%/year
Rail	6 - 8%/year
Water	5 - 10%/year

These estimates, based on predictions by various stone producers, assume a continuance of the present rate of inflation.

It should be noted that the lime industry could be affected greatly from the national concern for the environment. Specifically, the power industry may require large amounts of lime by 1980, in the form of an additive to control sulfur oxides from the burning of fossil

Table 4

Delivered Price of High-Calcium Limestone to Selected Power Plants

Power Plant	Location	Delivered Price ($/Ton)
Benning	Washington, D.C.	4.50*
Gorgas	Gorgas, Alabama	3.23
Cherokee	Denver, Colorado	6.36
J. McDonough	Cobb County, Georgia	4.50
Devon	Millford, Connecticut	4.50*
Fisk	Chicago, Illinois	2.40
R.S. Wallace	East Peoria, Illinois	3.30
Will County	Lockport, Illinois	3.30
D.H.Mitchell	Gary, Indiana	2.65
Wabash	Terre Haute, Indiana	2.25 (75-94% $CaCO_3$)
Riverside	Iowana, Iowa	1.95
Lawrence	Lawrence, Kansas	3.66
Cane Run	Louisville, Kentucky	3.00
Elmer Smith	Owensboro, Kentucky	3.72
Riverside	Baltimore, Maryland	3.85
Edgar	N. Weymouth, Massachusetts	4.50*
L Street	Boston, Massachusetts	4.50*
Delray	Detroit, Michigan	2.40
High Bridge	St. Paul, Minnesota	3.00
Hawthorn	Kansas City, Missouri	4.60
Sioux	West Alton, Missouri	3.10
Essex	Newark, New Jersey	4.50*
Port Jefferson	Port Jefferson, New York	4.50*
Waterside	New York, New York	4.50*
Allen	Belmont, North Carolina	5.39
Leland Olds	Stanton, North Dakota	13.20
Tidd	Brilliant, Ohio	3.80
Miami Fort	North Bend, Ohio	2.45
Acme	Toledo, Ohio	2.45
Horseshoe Lake	Horseshoe Lake, Oklahoma	8.00
Elrama	Elrama, Pennsylvania	5.55 (92% $CaCO_3$)
Schuylkill	Philadelphia, Pennsylvania	4.50*
Wateree	Rockland City, South Carolina	3.90 (88% $CaCO_3$)
Bull Run	Oak Ridge, Tennessee	4.24
Cabin Creek	Cabin Creek, West Virginia	6.00
Kammer	Captina, West Virginia	4.00 (80% $CaCO_3$)
Lakeside	St. Francis, Wisconsin	2.60

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*Source of stone is outside of U.S. (Bahamas) fuels. Although the amounts to be used are far from certain, it is possible that such pollution control efforts will make a significant new market for the lime industry.[15] New supply and demand relationships within this market could alter F.O.B. and transportation charges and have a considerable effect on delivered cost.

V. Conclusions

a. Enormous deposits of carbonate rocks occur in the United States and reserves are more than adequate for the foreseeable future. A very rough approximation of surface carbonate deposits indicates a minimum of 3.6×10^{12} tons, sufficient to satisfy national requirements for more than 500 years at the present rate of consumption (and assuming a 10 percent availability of these reserves). Availability of high purity stone may become a problem several decades hence, but, with the probability that the required quality will depend on other process and economic factors, no shortage of suitable stone is foreseen.

b. The major deposits of carbonate rocks occur in the eastern half of the United States where the vast majority of fossil fuel-fired power plants are located. Large reserves in these eastern areas provide a nearby source of stone for most power plants. Roughly two-thirds of all surface deposits of carbonate rock are found in the eastern half of the country.

c. Relative to the potential demand for carbonate rocks by power plants, production of these materials is quite large in most states. However, current production is inadequate to supply the potential needs of power plants in several Atlantic coastal regions, notably New England.

d. Limestone is the only type of carbonate rock which is produced in large enough quantities to merit consideration for wide-spread application in the removal of SO_2 from stack gases. In many areas ample amounts of other carbonate rocks are produced, particularly dolomite.

e. Most of the power plants in the eastern half of the United States could be supplied with high calcium limestone at less than $6.00/ton, many at less than $4.00/ton. Costs for power plants located in western states generally would be higher, owing to the lack of suitable, nearby deposits and other factors.

The preceding costs are based on an unsized, nominally 2"-6" x 0 stone (this indicates stone with a maximum size of 2"-6" and no minimum size), which is typical of the product from the primary crusher at most quarries. If a sized or fine material is desired, the cost may increase. Most quarries have little or no capacity for fine grinding, particularly in the amounts possibly required by the larger power plants.

f. Based on projections of material cost and transportation charges to 1975, the delivered price of limestone to most power plants is not expected to increase by more than $1.00-$2.00/ton.

VI. Recommendations for Application to Dry Limestone Injection and Other Limestone-Based Processes

The data and material contained herein and the referenced reports should be used to obtain a first approximation of the occurrence, characteristics, and cost of carbonate rocks in a particular case, thereby enabling a power company to assess the desirability of installing a limestone-based process for SO_2 removal. If further investigation is warranted, the state geological surveys, a list of which is included in the reference 14 report, individual stone producers, and local carriers should be consulted for more detailed and specific information.

Section C

Definitions[14]

To avoid some of the confusion which frequently results from the inexact and qualitative definitions applied to limestone and related materials in the United States, and from the multitude of overlapping names used, some of the terms as used in this section are defined below.

Limestone is a general term applied to sedimentary rocks composed chiefly of calcium carbonate, $CaCO_3$, calcium-magnesium carbonate, $CaMg(CO_3)_2$, or mixtures of the two. The term is also used, in a more restricted way, to denote rocks composed mainly of calcium carbonate, in order to differentiate them from dolomites. Dolomite is a name used to describe a limestone primarily composed of the mineral dolomite, calcium-magnesium carbonate $CaMg(CO_3)_2$. It is generally applied to carbonate rocks which contain approximately 20 percent or more magnesium carbonate, $MgCO_3$. Pure dolomite would contain 54.3 percent $CaCO_3$ and 45.7 percent $MgCO_3$. A point of contention, which is sometimes noted in the literature, is whether the calcium and magnesium carbonates are chemically combined, or whether they occur merely as a physical mixture. Limestone and dolomite occur with varying quantities of impurities, the most common of which are silica, alumina, iron oxides, and carbonaceous matter.

Lime can be defined as the product which results from calcination of a limestone or dolomite. Calcination is a process of heating the stone to a temperature at which carbon dioxide, CO_2 is released, thereby converting the carbonates to oxides. A calcium carbonate stone will produce a lime containing calcium oxide, CaO. Dolomite will produce a lime containing both calcium oxide and magnesium oxide, MgO, commonly called magnesia. In practice, commercial limes are usually derived from high purity stones containing a minimum of about 95 percent total carbonates.

The following list defines the more important terms used in this report:

Aragonite is a mineral composed of calcium carbonate, and having an orthorhombic crystalline structure.

Argillaceous limestone contains clay as a major impurity.

Bituminous (carbonaceous) limestone contains organic compounds as a major impurity.

Calcareous is a term used to describe any material containing calcium carbonate.

Calcite is a mineral composed of calcium carbonate, and having a rhombohedral crystalline structure. It is the predominant mineral in most limestones.

Chalk is a soft, friable, fine-grained limestone consisting primarily of the remains of minute marine organisms.

Coral limestone is a fossiliferous limestone consisting primarily of coral.

Dolomitic limestone refers to a limestone which contains more than approximately 20 percent magnesium carbonate. The term is usually interchangeable with "dolomite."

Ferruginous limestone contains iron oxides as a major impurity.

Flux stone is a high-purity limestone or dolomite used as a flux in metallurgical processes. It contains 95 percent or more minimum total carbonate.

Fossiliferous limestone is a stone in which the shells or shell fragments (fossils) are readily discernible.

High calcium limestone refers to a limestone which contains a minimum of approximately 95 percent calcium carbonate.

Magnesian limestone refers to a limestone which contains magensium carbonate within the approximate range of 5-20 percent.

Marble is a metamorphic rock consisting of crystallized grains of calcite and/or dolomite. Commercially, the definition includes any calcareous rock that can be polished.

Marl is an indefinite term used to describe a loose, soft, impure material which contains fine-grained fragments of shell and marine organisms intermixed with sand and clay.

Oolitic limestone contains small, rounded pellets (oolites), having a center of calcium carbonate or sand grains around which are deposited concentric layers of calcite.

Shell limestone is a term used to describe limestone derived from clam and oyster shells.

Siliceous (cherty) limestone contains silica as a major impurity.

Travertine consists of calcium carbonate that is chemically precipitated from hot springs.

Section D
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APPENDIX J

MATHEMATICAL MODELING OF THE LIMESTONE INJECTION PROCESS

In this appendix the author discusses the modeling activities which proceeded concurrently with the experimental work on which it is based. "The ultimate goal of this modeling was to establish a sound basis upon which the extensive data obtained at Shawnee could be used to predict performance and adapt the process to other boilers of different design."

His summary includes work by:

1. Professor Jack B. Howard, Department of Chemical Engineering, Massachusetts Institute of Technology
2. EPA Isothermal Kinetic Studies
3. Dr. Yoshimi Ishihara, Central Research Institute of Electric Power Industry, Japan
4. Dr. Robert W. Coutant, Battelle Memorial Institute
5. Professor Robert L. Pigford, University of California
6. Professor C. Y. Wen, West Virginia University

I. Introduction and Objectives

The unique adaptability of the dry limestone injection process to existing power plants—especially small and older units—together with its economic advantages in both capital and operating costs, made it imperative that a thorough evaluation of the process be made. At the time when this evaluation was undertaken (1967) by CSD in cooperation with TVA, there was strong evidence that good SO_2 removal efficiencies and high additive utilizations could be obtained by this process. A fundamental study made for EPA at the Battelle Memorial Institute in 1966 showed that high removal efficiencies were thermodynamically possible, but kinetic data and mass transfer correlations were not available by which limits of efficiency could be predicted *a priori*. An experimental program involving both boiler testing and fundamental research was necessary and many such investigations were carried out over the period 1967-70, both in the U.S. and other countries.

With the publication of reliable experimental data in 1969 on the reaction kinetics of CaO with SO_2 in both laboratory isothermal and dispersed-phase reactor systems, several efforts were begun to develop mathematical models which could be used to interpret the experimental data from various sources and guide optimization of performance in full scale tests. The ultimate goal of this modeling activity was to establish a sound basis upon which the extensive data obtained at Shawnee could be used to predict performance and adapt the process to other boilers of different design. Statistical correlations of data do not permit extrapolation with any degree of confidence to boilers different in design from that used to develop the correlation. A model useful for engineering design must account quantitatively for the effects of injection temperature, residence time, initial SO_2 concentration, sulfation, time-temperature profile, excess oxygen and other boiler characteristics which influence the kinetics of the reaction of SO_2 with the limestone particles injected into it.

Clearly, the development of a satisfactory model required that the primary rate-limiting mechanism (Battelle had already shown that there was no equilibrium limitation) be established. Although this is generally the first step in development of a comprehensive model, it is also the most critical, and was found to be the most difficult. Several possible and equally plausible assumptions were made as a basis for model development, but unfortunately, at the time when most of these modeling activities were begun, experimental research had not yet established the facts regarding the effects of all of the primary variables (temp., time, SO_2 concentration, particle size and physical properties of the calcine) upon the reaction characteristics with SO_2. Consequently, models based upon different assumptions were developed, and only by comparing the responses predicted by the model with those observed experimentally can a judgement be reached regarding the most valid and useful model of the limestone injection process.

In the summary following, somewhat of a historical presentation is provided since the modeling activities proceeded concurrently with the experimental work on which it is based. The development of information identifying the importance of key parameters is emphasized and integrated, via discussion, into the most general basis for interpretation and definite conclusions.

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II. Summary of Modeling Activities

Professor Jack B. Howard, Department of Chemical Engineering, Massachusetts Institute of Technology

At the request of EPA, a project was undertaken in August 1969 to identify the rate-limiting mechanism controlling the sorption of SO_2 by calcined limestone. On the basis of the known physical properties of such calcines the rate of diffusion of SO_2 into the pore structure of individual particles was to be estimated by means of the well-developed theory of heterogeneous catalysis. By calculation of the pure diffusional resistances and comparison with experimental data, the importance of chemical reaction, pore diffusion and other SO_2 sorption resistances were inferred.

The model[1] describes the reaction behavior of a porous limestone particle in terms of the reaction of clusters of microscopic nonporous CaO grains that comprise the larger particle. It accounts for the effects of pore size, porosity, internal surface area and CaO content. The pore spaces between grains permit access of SO_2 to the grain surfaces for reaction while larger pores between grain clusters provide the main path of diffusion into the particle. Four resistances are considered: (1) transport of SO_2 from the ambient gas to the particle surface, (2) diffusion of SO_2 within the pores, (3) chemical reaction at the grain surface and (4) diffusion of $CaSO_4$ reaction product into the solid CaO grains.

The resistance due to mass transfer to the particle surface was eliminated as a possible limitation by comparison of experimental data from Battelle's dispersed reactor with the calculated rate of mass transfer through the gas film. The results (Figure 1, Curves A and B) showed that the quantity of SO_2 that can be transferred to 90 μ particles would permit 25% CaO conversion in 2 seconds at 1800° F. Actual data at these conditions show only 9% conversion, consequently Howard concluded that the major resistance is within the particle itself, resulting from either pore diffusion or chemical reaction.* Ishihara[2] reached the same conclusion on the basis of calculations of the decrease in SO_2 concentration through the gas film surrounding dispersed particles.

Two versions of the model were tested against experimental data on the isothermal sorption of SO_2 by calcines prepared in the laboratory. One version holds the pore structure constant except for surface area, which decreases in proportion to conversion. The second version of the model allows the pore structure to change as the reaction progresses, thus accounting for the expansion of the CaO grains as they are converted to the more voluminous $CaSO_4$. Calculations with the two versions show that the sorption characteristics are relatively insensitive to porosity in comparison with the effects of grain size or surface area. Detailed analysis of experimental data with the model indicated that the

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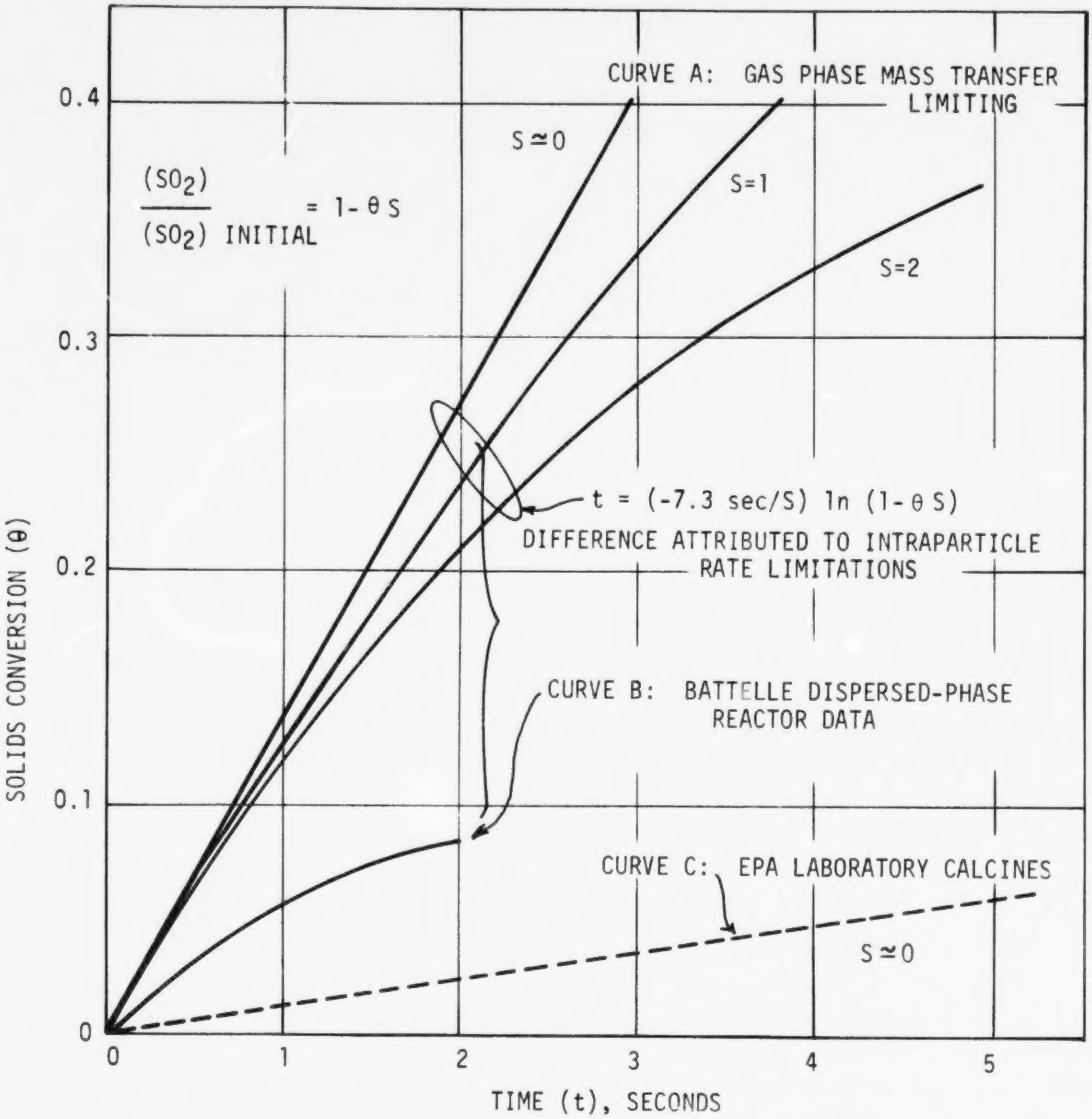
*Although the Battelle data are at low particle to gas concentrations, it has been shown that the reported rates are in good agreement with Ishihara's pilot plant data for similar sized particles, which were obtained at particle-to-gas stoichiometries up to 2.5 x (3).

FIGURE 1



PREDICTED BEHAVIOR OF PARTICLES REACTING WITH SULFUR DIOXIDE UNDER EXTERNAL DIFFUSION CONTROLLED CONDITIONS COMPARED WITH EXPERIMENTAL DATA (1,000°C; PARTICLE SIZE 96 μ ; 3000 PPM SO_2; S = INITIAL MOLES SOLID/STOICHIOMETRIC MOLAR SOLID overall rate is controlled jointly by the pore diffusion and chemical reaction rates, with pore diffusion being the stronger. The estimated Thiele modulus of the smallest particles was about 30 indicating $\eta < 0.1$, consequently the reaction profiles predicted by the mode for particle cross sections in all cases showed only the external surface zone to be participating.

A unique feature of this model is its allowance for solid diffusion. Howard's analysis showed that without diffusion of the $CaSO_4$ into the CaO grains, the maximum solid conversion could not exceed 8%. It is interesting to note that the data analyzed with the model indicates that diffusion through the solid grain was rapid enough to contribute little to the overall resistance.

The most significant conclusion from the MIT analysis was that the internal surface area available for reaction was the primary factor limiting SO_2 sorption rate and that the reaction behavior could be approximated with knowledge only of the effective CaO grain radius. A comparison between the reaction rates obtained with the EPA laboratory calcines examined in this study and the rate obtained when limestones are injected into and dispersed in flue gas (Figure 1, curves B and C) showed a significantly higher rate in the latter case. No explanation for this difference could be offered on the basis of information available at that time.

EPA Isothermal Kinetics Studies

The extreme discrepancy between reaction rates measured in the laboratory and the rates observed for limestone particles of the same size injected at the same temperature in dispersed systems had been known since the publication of isothermal kinetics data in 1969[4,5]. This discrepancy, and the lack of an adequate explanation for it, was the primary limitation upon the development of a fundamental model which could be applied to predict performance on the basis of reaction kinetics.

Research continued at EPA concentrating upon the physical properties of the calcines affecting reaction rate, i.e., pore structure of the calcine and properties of the original rock. The results of these additional experimental studies, reported at the 1970 symposium, established the relationship between reaction rate and the surface area of the calcine. Dr. Dennis Drehmel[5] showed that the reactivity of calcines prepared in the laboratory were strongly correlated to the BET surface area, which varied according to calcination temperature. Borgwardt[7] verified these findings by quantitative measurement of the reaction rate of calcines prepared from different types of rock (which yielded different pore structures and surface areas) and showed that the initial reaction rate was a linear function of the BET surface area of the calcine.

A simple model based on chemical reaction control was shown to correlate the initial rates of SO_2 sorption of calcines of different types of rock prepared at a given calcination temperature, and the rates of a given rock type calcined at different temperatures:

$$r_o = k_s S_g C_{SO_2} \eta \tag{1}$$

where r_o is the rate per unit mass of CaO extrapolated to zero sulfation, and Sg is the B.E.T. surface area of the calcine.

The reaction rate constant, $k_s = Ae^{-E/RT}$

The activation energy for different calcines averages about 17 k cal/g mole. The intrinsic reaction rate constant was accurately measured at 900°C at 0.22 cm/sec, essentially independent of stone type.

The effect of sulfation was shown to result in an exponential decrease in isothermal reaction rate with conversion, X according to:

$$r = r_o e^{-\beta x} \tag{2}$$

The coefficient β is a strong function of particle size, since it includes the effectiveness factor, η, and is a weak function of stone type, probably due to the differences in solid diffusion rates within CaO grains postulated by Howard. This effect was quite small however, compared to the effect of surface area upon the overall rate of SO_2 sorption.

The maximum limit of CaO conversion (total SO_2-sorption capacity) was defined by the available pore volume for product accumulation. This was determined by measurement of grain expansion and decrease in pore volume with conversion, which showed that calcines of maximum theoretical pore volume can achieve no more than 49% CaO conversion. At that point the entire pore volume is filled with reaction product, and greater conversions can be achieved only by solid diffusion through the exterior particle surface, which is extremely slow.

Dr. Yoshimi Ishihara - Central Research Institute of Electric Power Industry, Japan

Establishment of the direct relationship between BET surface area and initial SO_2 reaction rate provided the first insight into the mechanism of SO_2 capture by the limestone injection process. At the same symposium where those data were presented, Dr. Ishihara reported[2] the results of an extensive investigation of the reaction kinetics in a pilot-scale limestone injection furnace. As a part of his experimental study, measurements of the BET surface areas were obtained for calcines prepared by rapid (less than 5 seconds) calcination in the dispersed system. Ishihara's data clearly showed that the surface areas developed in these short exposure times are considerably greater than the surface areas of calcines prepared in the laboratory at the same temperature (which require longer periods of calcination to achieve complete conversion of $CaCO_3$ to CaO). The surface areas produced by calcination in the dispersed phase were 20-30 m^2/g, an order of magnitude greater than that of laboratory calcines. This difference in surface areas* provided the basis for reconciling the discrepancies between reaction rates measured in isothermal laboratory experiments and the observed reaction rates in dispersed systems. Good correlation of the two independent sets of data was in fact later achieved.

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*The existence of large surface areas immediately following dissociation of $CaCO_3$ had been previously postulated by Mayer & Stowe[8] from consideration of molecular rearrangements that must occur when unit crystal cells are altered to the CaO configuration. Absolute surfaces as great as 10^3 m^2/g were estimated.

Although Ishihara's objective was not specifically that of modeling the reaction, he did quantitatively evaluate the effect of each process variable—in much greater detail than was done in any other pilot plant study. He correlated his data according to the simplest possible model for chemical reaction control,

$$r = \frac{d(\text{CaO conversion})}{dt} = k\, C_{SO_2} \tag{3}$$

$$\text{where } k = Ae^{-E/RT} \tag{4}$$

$$\text{and } T = f(t)$$

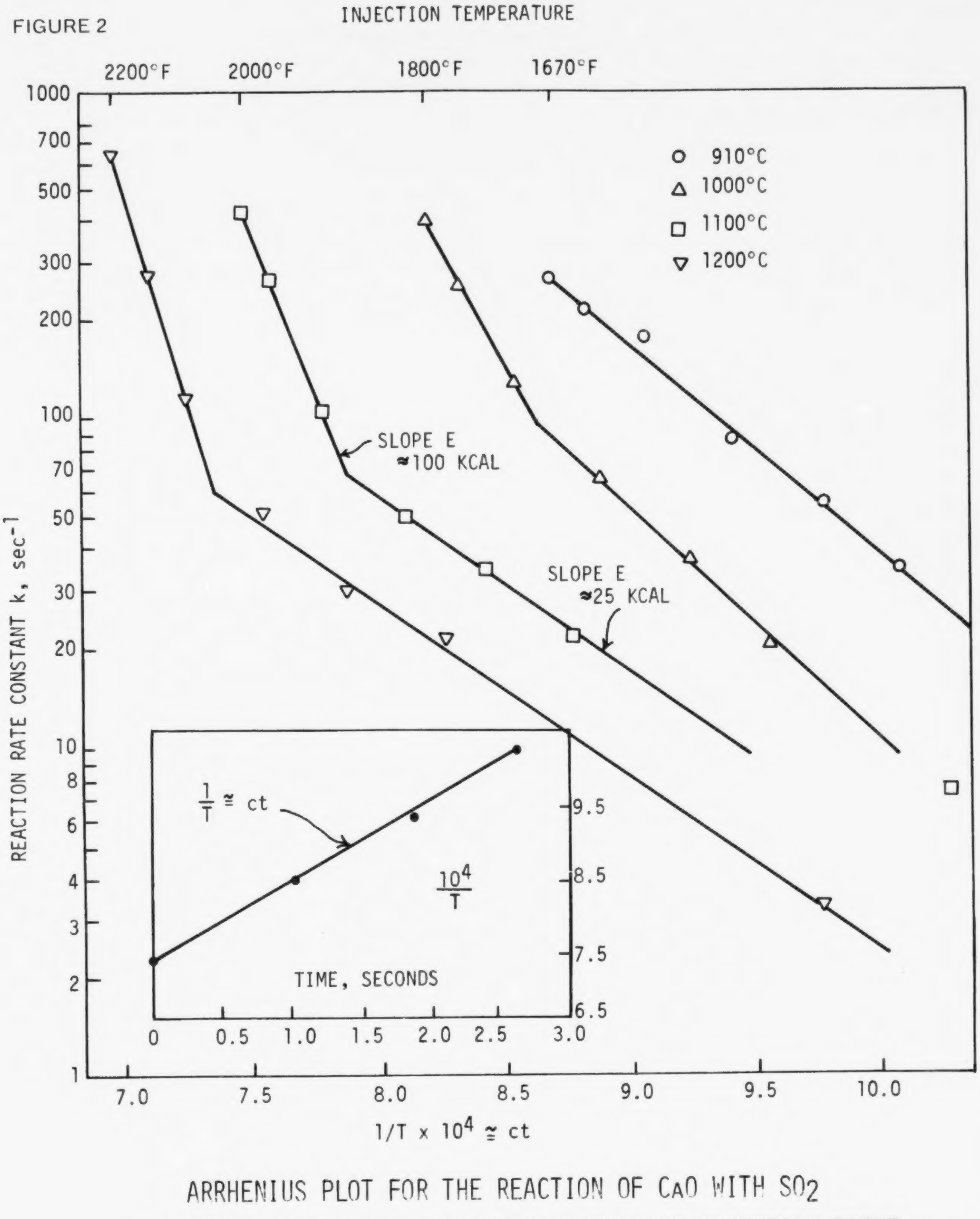
Comparison of this model with equations (1) and (2) shows that it is the same as that used successfully to correlate the initial isothermal rate data for precalcined stones, where $k = k_s S_g$.

Ishihara determined the value of k as a function of each of the major process variables: temperature (time), particle size, SO_2 concentration, limestone type and injection temperature. He analyzed his data on the basis of instantaneous rates measured at a given value of temperature (time) in the reactor. This approach assumes that the rate is a function only of temperature and SO_2 concentration, i e., that the rate at $t > 0$ is independent of sulfation and surface area. It should be noted that surface and sulfation effects are, therefore, reflected in the factor A in equation (4), which will also be a function of temperature and time if these effects are significant.

This simple model proved to be an extremely effective tool for the qualitative analysis of limestone injection data. Figure 2 shows a plot of the reaction rate constant as a function of the instantaneous temperature and injection temperature. Several important responses are revealed by this plot. The slope of each line reflects the activation energy of the reaction and also any effect of sulfation and/or surface area. Considering the straight line representing injection at the lowest temperature (910°C) it is clear that the rates are a linear function of temperature over the full (order of magnitude) range of reaction rates observed. One may thus conclude that sulfation alone has a minor effect on the apparent activation energy. Otherwise the slope of this line would change with 1/T (and time), reflecting the effect of accumulated sulfate. The observed independence of activation energy from sulfation effects is in accord with Howard's conclusion regarding the constancy of activation energy over a broad range of conversion for the isothermal reaction of CaO with SO_2.

Comparing the 910°C curve with the other curves in Figure 2, representing higher injection temperatures, it is clear that the slope increases with temperature. Since sulfation has a negligible effect on apparent activation energy (slope) it is clear that the rapid deactivation indicated by the change in slope with injection temperature is a result of factors other than sulfation. Ishihara attributed this change to the loss of surface area at high temperature and to internal diffusion resistances as sulfation progressed. In view of the above discussion regarding the effect of sulfation on activation energy, surface area is clearly

FIGURE 2



ARRHENIUS PLOT FOR THE REACTION OF CaO WITH SO_2
SHOWING THE EFFECT OF GAS TEMPERATURE AT INJECTION POINT

the primary factor responsible for the observed change in reaction rate with temperature. As additional evidence of this fact it should be noted that the apparent activation energy in the final stage (about 25 K cal), where the effect of temperature no longer influences surface area, is the same magnitude as the activation energies measured in the laboratory for calcines of fixed pore structure.

It is informative to put Ishihara's model in integrated form for comparison with the other models. Equations (3) and (4) are not directly integrable, however, as shown in Figure 2, a plot of Ishihara's data for the time-temperature profile of his reactor[2] shows that 1/T can be approximated accurately over the short time periods used in his experiments by

$$\frac{1}{T} \cong ct$$

so that

$$\frac{dx}{dt} \cong Ae^{-Ect}$$

where E is the apparent activation energy, or slope, of the lines shown in Figure 2. Integrating,

$$X \cong -\frac{A}{E_c} e^{-Ect} + C$$

since x = 0 at t = 0, C = A/Ec and

$$X \cong \frac{A}{EC} (1-e^{-Ect}) \qquad (5)$$

As is evident from the previous discussion,

$$A = f(Sg, C_{SO_2})$$

A comparison of equation (5) with that derived independently by Coutant using emperical curve-fitting techniques will be made in the next section.

Dr. Robert W. Coutant - Battelle Memorial Institute

Fundamental experimental studies[9] of reaction kinetics in a dispersed phase reactor were begun at Battelle in 1967 under CSD sponsorship and continued through 1971. The reactor used in this investigation was designed specifically to permit close control over the reaction variables and to permit independent study of each variable upon the reaction kinetics. Its unique features were (1) particles could be reacted at constant SO_2 concentration and (2) particles could be injected and collected over varying residence times from 0.2 seconds to over 2 seconds thus both calcination and sulfation could be followed directly by particle analysis.

Following Ishihara's report in 1970, the Battelle research was directed specifically toward verification of the effects of surface area on SO_2 reaction suggested by Ishihara's data. A series of experiments in which limestone particles were "flash calcined" over varying ranges of time and injection temperature (with no SO_2 present in the flue gas) soon confirmed the existence of large BET surface areas immediately following calcination and further showed that the surface decreased rapidly with residence time. For example, 90 μ particles injected at 1950°F yielded surface areas of 60 m^2/gCaO in 0.2 second residence time, which decreased to 30 m^2/gCaO after one second.

The BET surface areas and corresponding SO_2 reaction rates obtained in the Battelle reactor were compared with the isothermal reaction rate-surface area data obtained from the EPA differential reactor experiments. The results of this comparison, shown in Figure 3, demonstrate excellent correlation between the two sets of data. The agreement confirmed that the high reaction rates observed in the non-isothermal dispersed system is predicable from its surface area and the intrinsic chemical reaction rate constant (0.22 cm/sec at 980°C) measured in the laboratory. The agreement also indicates that chemical reaction is the primary limitation on the initial rate of SO_2 absorption by the dispersed particles, verifying the absence of gas-phase mass transfer limitations as inferred by Howard and Ishihara from independent consideration. Clearly, the maximum rate is determined by chemical reaction rate, and consequently, also by surface area.

The development of mathematical models of both the sulfation and calcination reactions was an objective of the Battelle project. The approach used in modeling the sulfation step did not presuppose any specific reaction controlling mechanism. The observed responses of sulfation, S, vs. time were fitted empirically to obtain the best correlation with time and temperature. Unfortunately, only one particle size, 90μ, was modeled. Coutant expressed the results in the form[10]:

$$s = b(1 - e^{-kt}) \tag{6}$$

where

$$k = \exp(14.563 - 18734/Tm) \tag{7}$$

$$b = \exp(-2.982 + 10139/Tm) \tag{8}$$

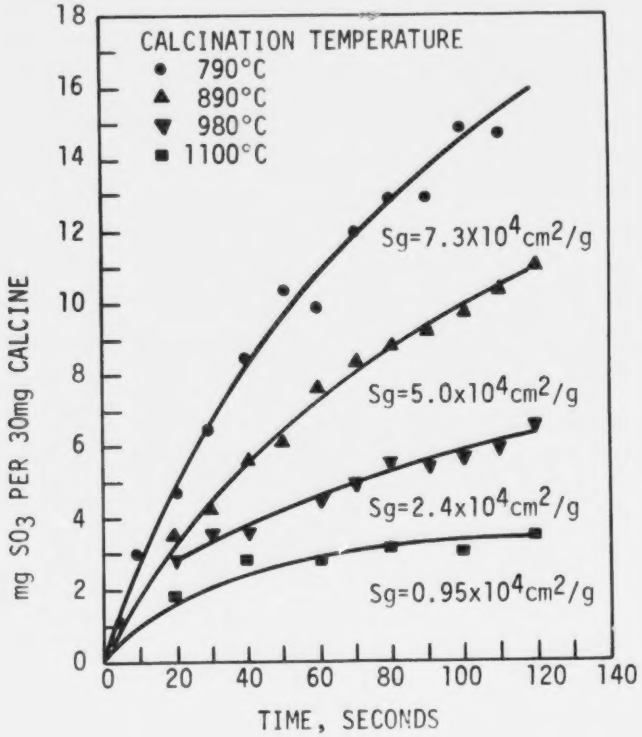
It should be noted that Coutant's model expresses the coefficients in terms of mean reactor temperature, Tm, rather than the instantaneous temperature at time t.

Comparison of equation (6) with the integrated form of Ishihara's chemical-reaction control model Equation 5 shows that they are identical if b = A/Ec and k = Ec. The injection-temperature dependence of the slope of Ishihara's curves, Ec, is confirmed in Coutant's equation (7). Likewise the dependence of Ishihara's coefficient A/Ec on temperature in an inverse manner from Ec is reflected by equation (8). The primary features of both sets of data are summarized by the same basic model which requires no assumption more complex than chemical-reaction control to explain all observed effects.

The coefficient b was identified by Coutant as the maximum (terminal) conversion achievable under given injection conditions. The value b decreased with increased injection temperature and since A = bk, Ishihari's factor A also decreases with increasing injection temperature, thus reflecting the effect of loss of surface area on the overall reactivity. Thus, for 90μ particles,

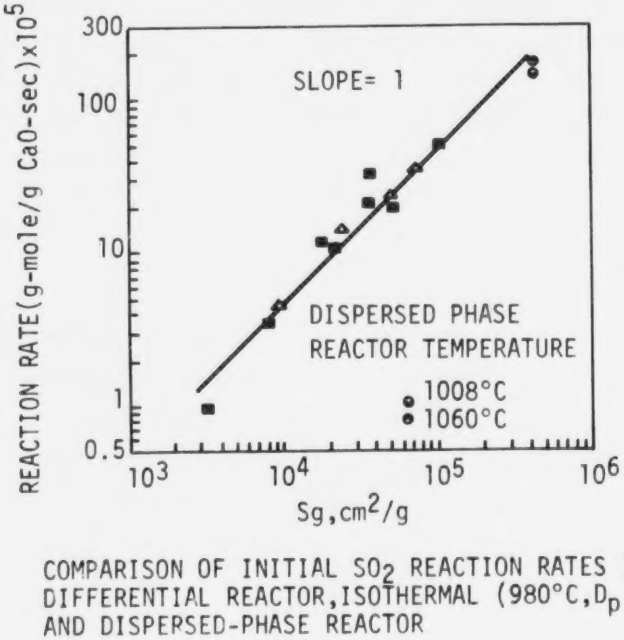
$$A = f(Sg) = 2.45\, e^{-8595/Tm}$$

FIGURE 3



ISOTHERMAL SORPTION OF SO_2 BY TYPE 4 LIMESTONE AS A FUNCTION OF SURFACE AREA OF ITS CALCINE.

REACTION TEMP=760°C;PARTICLE SIZE=0.0096 cm;SO_2=3000 ppm



COMPARISON OF INITIAL SO_2 REACTION RATES IN DIFFERENTIAL REACTOR,ISOTHERMAL (980°C,D_p =0.0096 cm) AND DISPERSED-PHASE REACTOR

SO_2 = 3000 ppm

This loss of surface area at high temperatures is brought about by the growth of the CaO sub-grains that comprise a lime particle, which has long been known to be an activated process[11], i.e., the rate of grain growth increases with temperature. The resulting loss of surface areas (which is inversely proportional to grain size) of calcines prepared at different temperatures has been demonstrated by Drehmel[12] and Chan et al.[13] for calcines prepared in the laboratory.

The Battelle model thus shows that for a given particle size, surface area decreases with time and that the rate of change increases with injection temperature. Examination of the Battelle data also shows that the rate of change is dependent upon particle size. The comparison of terminal BET surface areas of 90μ particles and 48μ particles calcined in the dispersed phase reactor show a marked reduction in surface of the smaller particles:

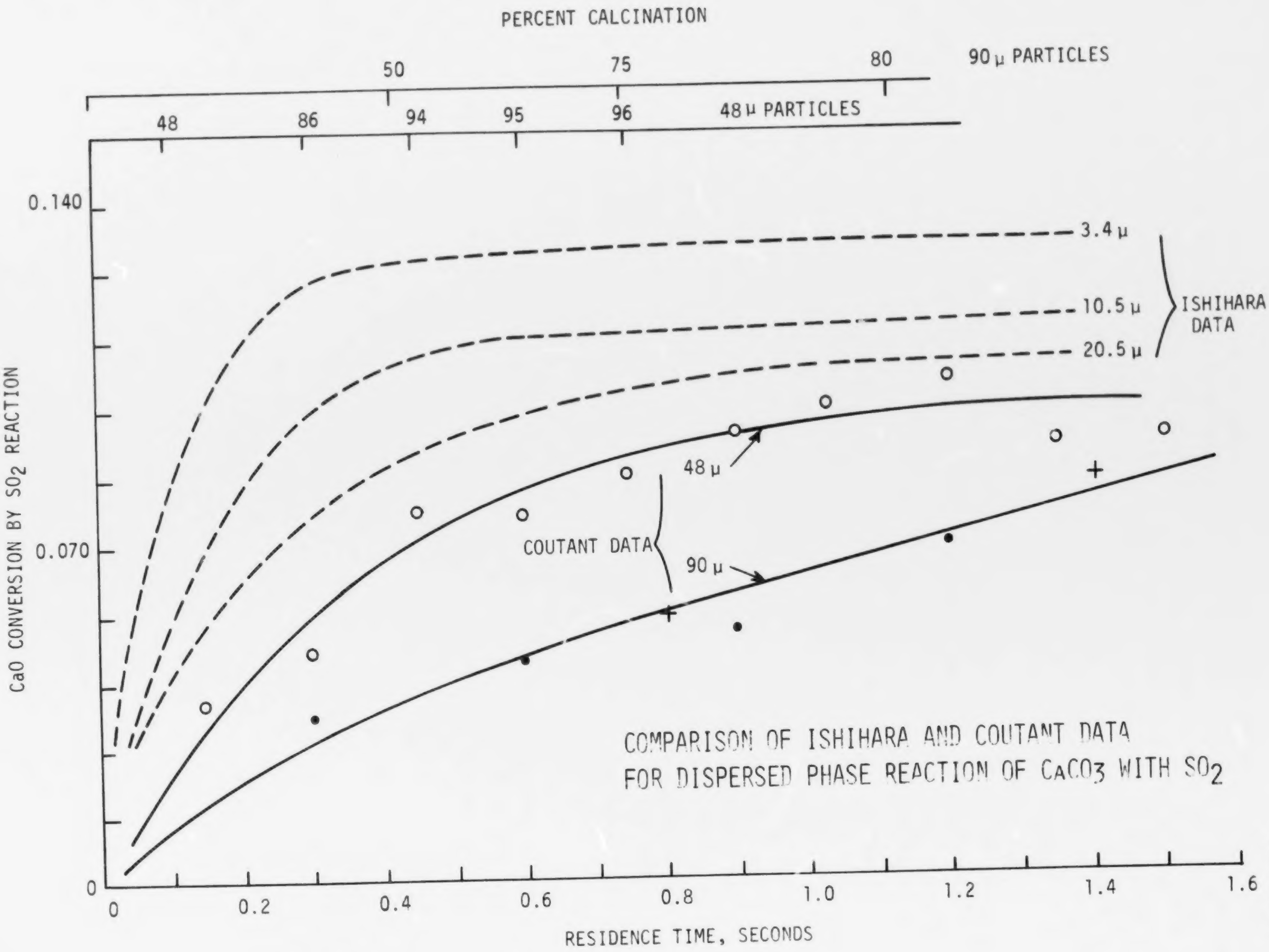
Table I
Effect of Particle Size on Terminal Surface Area

Particle Size, Microns		Injection Temp. °F	Residence Time, Sec.	Terminal BET Surface, m^2/g	Run No.
90	FW	2224	1.27	21.5	925-B
48	FW	2243	0.99	7.6	106-F
90	FW	2224	2.86	21.3	675-A
90	1336	2155	1.17	23.7	317-C
48	1336	2140	2.08	14.2	226-B
48	IGS4	2140	2.08	8.6	32-A

That the small particles would calcine more rapidly than large ones is in accord with the established unreacted-shrinking core mechanism by which calcination proceeds, i.e., calcines from the outer particle surface inward toward the particle center. Consequently, the small particles which have greater particle surface per unit mass, generate greater BET surfaces per unit time during calcination and of course, complete calcination sooner. This fact is clearly shown by the Battelle calcination rate data reproduced in Figure 4.

The overall effect of this dependence of calcination rate on particle size is dramatically demonstrated by comparing the Battelle data with Ishihara's data for the SO_2 reaction, which together covers a particle size range from 90μ to 3.4 μ. Figure 4 demonstrates the remarkably good agreement between the two sets of data when directly compared. Remember that these data were obtained from completely different reactor designs, operating at vastly different injection stoichiometries, and that one set of data was obtained by gas analysis while the other set was obtained by particle analysis. This comparison should be particularly noted by those who have despaired over apparent lack of consistency among results of various investigators of the limestone injection process. All of the essential features of the dispersed reaction are reflected in these curves: the increase in initial rate as particle size is reduced, resulting from higher rates of surface generation, the flagging of the reaction in smaller particles when calcination is completed and overburning

FIGURE 4



COMPARISON OF ISHIHARA AND COUTANT DATA FOR DISPERSED PHASE REACTION OF $CaCO_3$ WITH SO_2

occurs. The rate of flagging clearly increases as particle size is reduced, reflecting the rapid loss of surface area and reaction rate by the small particles. The overall result is a very small gain in terminal conversion despite a 30 fold decrease in particle size.

The flagging of the reaction when particle size is reduced is the most critical feature of the limestone injection process, as it determines the ultimate limit of CaO conversion (and SO_2 removal efficiency) that can be obtained by injection into the boiler furnace. The fact that the dispersed phase reaction ceases after a fraction of the total residence time available has been reported in the pilot injection studies of Juntgen[14], Peabody Coal[15], Florida Power/EPA[16], Babcock & Wilcox[17] as well as the data discussed here. Previous attempts to account for this flagging have generally assumed that product shell formation was responsible. This assumption is not consistent, however, with the small gain in terminal conversion. If shell diffusion were limiting SO_2 sorption at the terminal point, the total conversion would increase in direct proportion to the reduction in particle size. The assumption of shell diffusion is also inconsistent with the activation energies observed by both Coutant and Ishihara, which exceed that of diffusion by an order of magnitude.

The effect of SO_2 concentration has been shown by both Coutant and Ishihara to have only a slight effect on terminal CaO conversion in the dispersed system. Each investigator showed that CaO conversion increased approximately with the 1/2 power of initial SO_2 concentration. Ishihara concluded that the instantaneous reaction rate follows a first order response to SO_2 concentration, in agreement with isothermal kinetic measurements[4,18,19]. The effect of SO_2 concentration cannot be evaluated independently of the other factors in the Battelle model, in which it appears as part of the factor b, which includes surface area. Ishihara, by measuring instantaneous rates at different SO_2 levels, was able to separate out the surface area effect. The evidence, therefore, suggests that the reduced overall effect of SO_2 results from the change in surface area with time and its cumulative effect upon the chemical reaction rate.

Professor Robert L. Pigford, University of California

This model[20] is based upon fundamental descriptions of processes occurring within a lime particle during SO_2 sorption. Like the MIT model it considers the particle as an assemblage of nonporous CaO grains surrounded by interstices through which SO_2 diffuses prior to reaction at the grain surface. The model assumes the overall rate to be controlled by diffusion through this pore structure coupled with diffusion through a product layer which forms on the CaO grains as the reaction proceeds. Chemical reaction at the grain/shell interface is assumed to be so rapid that it contributes no resistance to SO_2 sorption. The model, like the MIT model, considers grain size and pore structure to be a function only of conversion and independent of temperature or time.

The model accounts for variation in the extent of participation of the interior grains depending on pore structure and position within the particle. In the extreme cases where pore diffusion controls or grain product-layer diffusion controls, the model reduces to two basic forms that correspond to a particle surface reaction or a particle volume reaction.

Case 1 - Superficial surface reaction:

SO_2 sorption rate $= 13.6\,(\alpha^{1/2} D^{1/2} D_s^{1/4} S_v^{1/2} \Gamma_s^{1/2} R^2 C_o^{3/4} / \tau^{1/2} t^{1/4})$
per particle
or, Rate per $\propto D^{1/2} D_s^{1/4} S_v^{1/2} C_o^{3/4} (\tau^{-1/4}) R^{-1}$
unit mass

This form of the model predicts that conversion will be proportional to exposure time to the 3/4 power for the situation where pore diffusion is the predominant resistance.

Case 2 - Total surface (volumetric) reaction:

SO_2 sorption rate $= 5.5\,(D_s^{1/2} S_v \Gamma_s^{1/2} R^3 C_o^{1/2} / t^{1/2})$

or rate per unit mass $\alpha\ D_s^{1/2} S_v C_o^{1/2} (t^{-1/2})$

In this case, where grain-shell diffusion is the predominant resistance, the model predicts conversion to be proportional to exposure time to the 1/2 power.

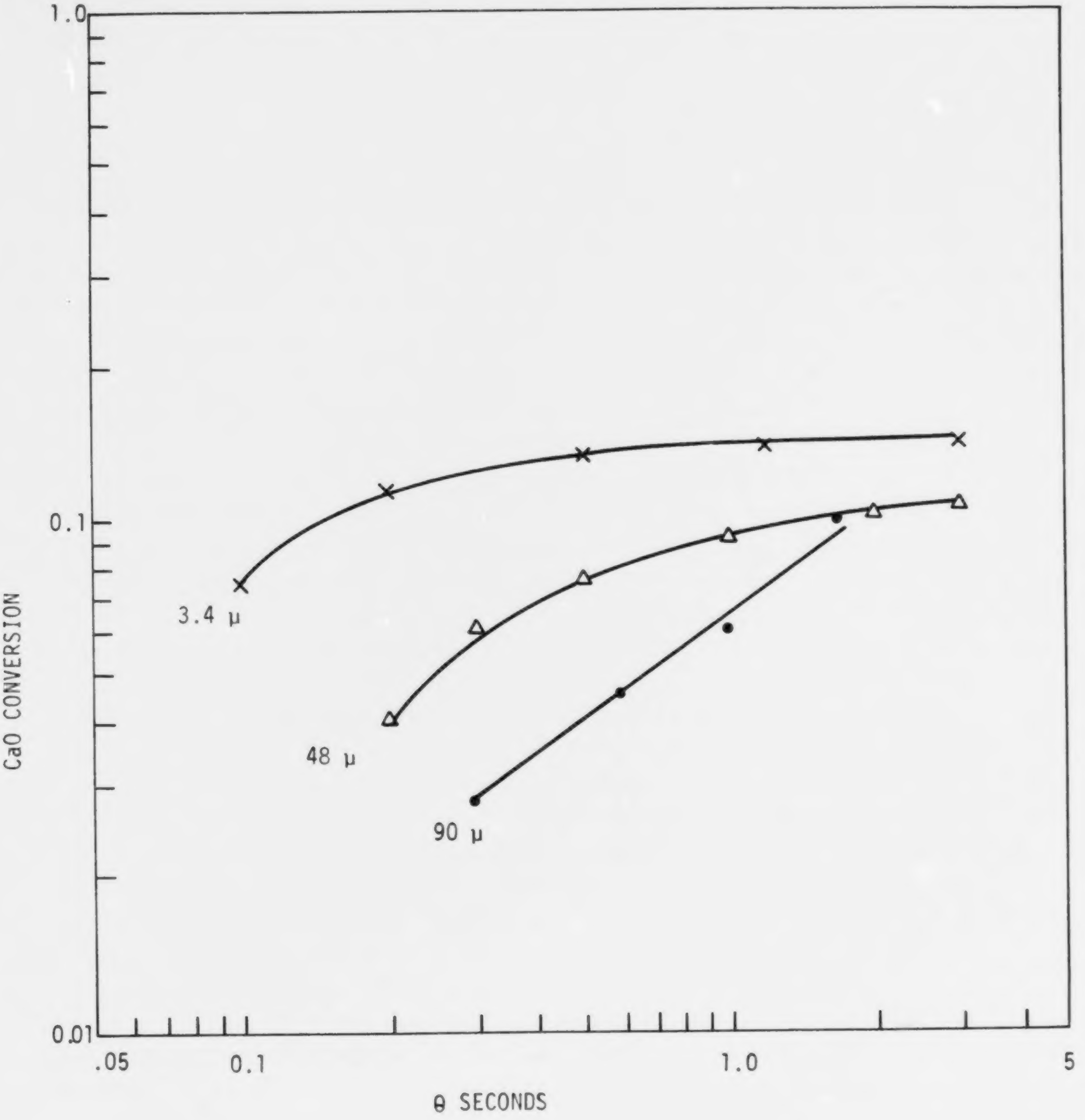
Pigford tested the model with Coutant's dispersed-phase reactor data by plotting log conversion vs. log time for 90u particles. He obtained a straight line of slope 0.64 and, by comparing this slope with the model predictions of 0.5 and 0.75, concluded that SO_2 sorption was controlled jointly by pore diffusion and grain shell diffusion. He did not test the model with particles smaller than 90μ.

Figure 5 is a plot of Coutant's data for 48μ particles that were discussed in Figure 4. It is clear that the predicted linear relationship does not hold, nor is it valid for Ishihara's data on smaller particles. The comparison indicates that conversion increases less rapidly than would be predicted for either pore diffusion, or grain-shell diffusion. The only remaining resistance to which this behavior can be attributed is chemical reaction.

Further examination of Pigford's equations show that the influence of temperature upon SO_2 sorption rate can be accounted for only by its effect upon the diffusion coefficients D and D_s. As noted by Howard, these coefficients are very weakly affected by temperature, showing a maximum temperature dependence of $T^{3/2}$, which corresponds to an apparent activation energy of 3.5 k cal at 1800°F. As pointed out in the previous discussion, both Ishihara and Coutant obtained activation energies of about 30 k cal for the dispersed phase reaction. Likewise, the activation energies determined for the isothermal reaction[4,18,7,22] of CaO have established that the reaction is far more sensitive to temperature than diffusion would permit.

It must be concluded that the Pigford model does not adequately describe the observed effects of particle size or temperature. The model is useful, however, to the extent that it affords additional proof that chemical reaction is rate controlling.

FIGURE 5



TEST OF PIGFORD MODEL WITH 3.4 AND 48 MICRON PARTICLES

Professor C. Y. Wen, West Virginia University

After extensive review of isothermal reaction rate data, including experiments conducted in the Chemical Engineering Laboratory of West Virginia University, Ishida and Wen formulated a model based upon the zone reaction concept[21]. The lime particle is again visualized as an assemblage of CaO grain to which SO_2 diffuses through the pores between grains. Whereas Pigford coupled pore diffusion with diffusion through a product shell on the grain surface, Wen coupled it with chemical reaction at the interface between the product layer and the unreacted grain core. Wen's model is unique in that it has been applied to the correlation of both isothermal laboratory data, and non-isothermal data from dispersed systems, including full scale boiler injection. It has successfully correlated the observed reaction rates from all of these sources.[22]

The chemical reaction rate is expressed in terms of the reaction rate constant per unit surface and the surface area per unit volume of lime. The latter is determined by the radius of the unreacted core, r_c, within the CaO grain at time t. Thus, when the original grain radius is R', and the particle size is small enough for SO_2 concentration to equalize throughout the particle volume,

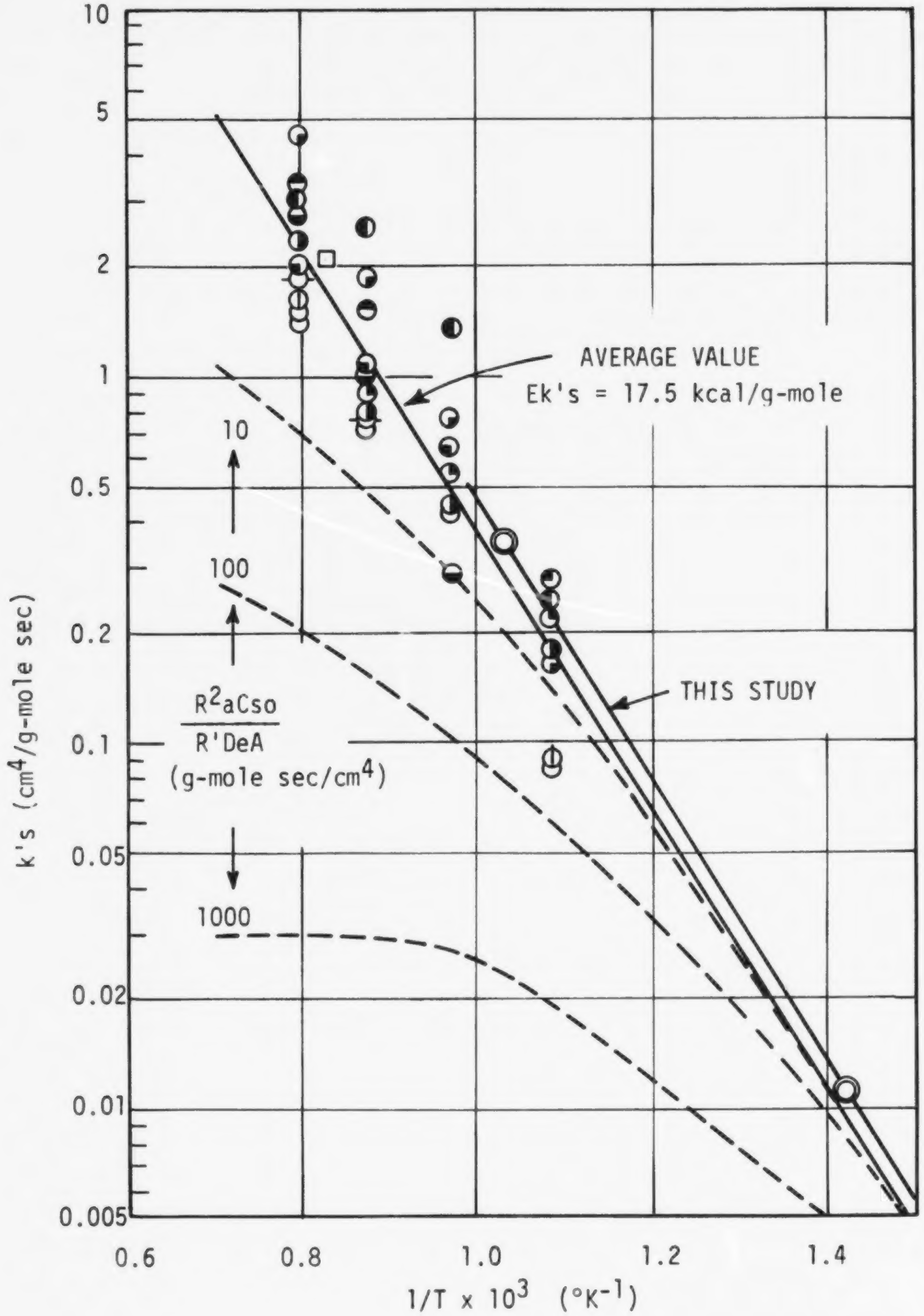
$$\text{rate per unit mass CaO} = \frac{3}{(R')^3}\, k_s\, C_{SO_2}\, r_c^2 \qquad (9)$$

Since $r_c = R'$ at $t = 0$, the initial rate is inversely proportional to BET surface area. At low conversions and small particle size the model thus reduces to the same form used by EPA to correlate isothermal data.

A more complex form of the model can be applied to large particles in which diffusion effects are also important. The theory of gas-solids reactions in which diffusion and reaction occur simultaneously was rigorously developed by Prof. Wen over the period 1967-71. By comparing observed reaction rates with the theoretical curve for particles of different diameter, Wen was able to estimate the diffusion modulus for the isothermal reaction of SO_2 with calcined limestones. The model also enabled him to separate out the intrinsic reaction rate free from diffusional effects. The reaction rate constant was thus evaluated for data from varying sources over a wide range of temperatures as shown in Figure 6. The value of the reaction rate constant and activation energy is established by this correlation and can be directly applied to the modeling of non-isothermal systems.

A complete simulation of the limestone injection in process was carried out[22] on the basis of the above model, using data from the Shawnee full scale boiler tests. Simulation inputs included the time-temperature profile of the Shawnee boiler, the average particle size of the limestone, the kinetic parameters established in isothermal studies and an assumed mean CaO grain size of $0.02\ \mu$. A comparison of the results predicted by the simulation and the results obtained at Shawnee are shown in Figure 7. It is evident that the model is capable of predicting boiler test results within about 30 percent at the current level of refinement of model and assumptions.

FIGURE 6



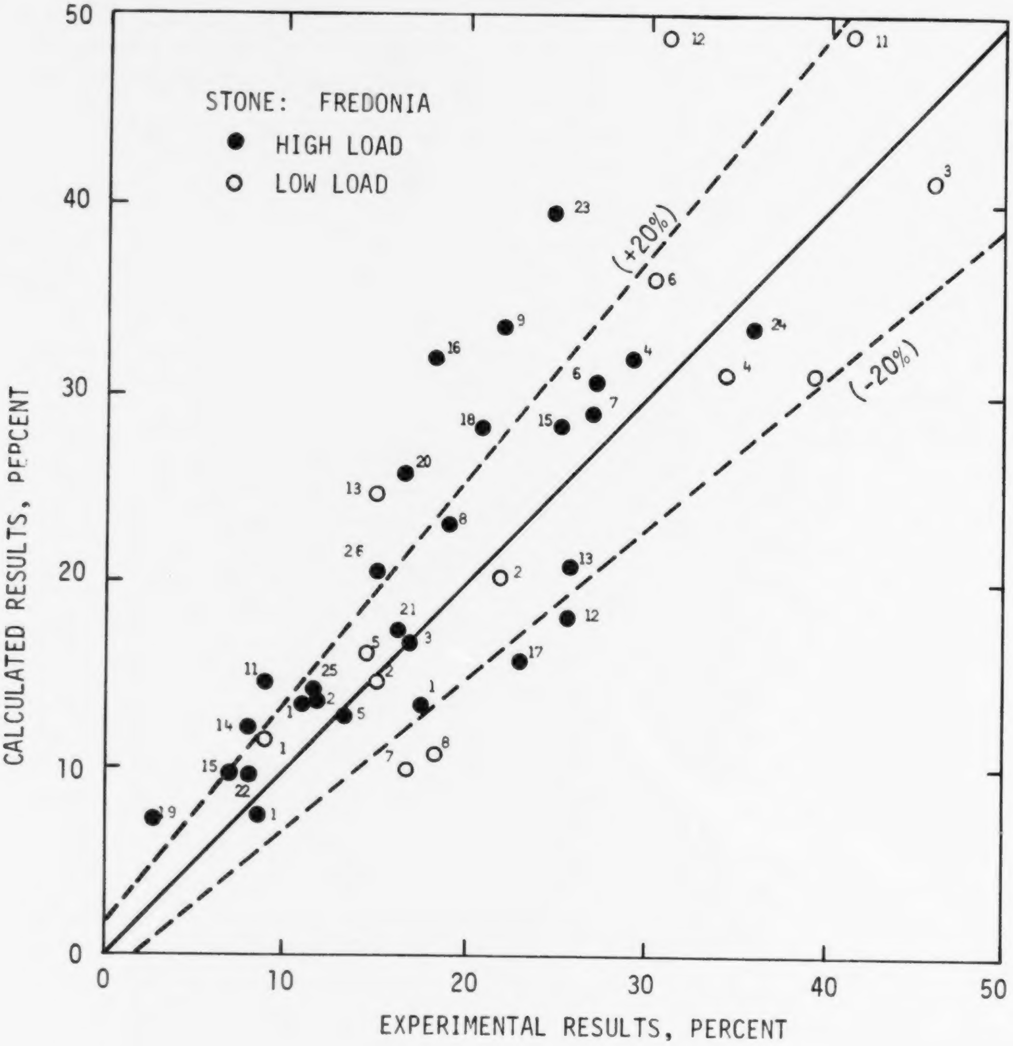
RATE CONSTANT FOR THE GRAIN REACTION (WEN)

(KEY TO FIGURE SHOWN ON TABLE II)

Table II
List of Types of Limestone Particles Examined
and Corresponding Keys Used in Figure 6
(C: calcined stone, R: raw stone)

Investigator	Key	Form	Type Stone	CaO (wt% in calcine)
Borgwardt[4]	◔	C	Dolomite	55
	◶	C	Limestone	54
	◵	C	Limestone	94
	◴	C	Limestone	81
Borgwardt[7]	◓	C	Calcite spar	98
	◒	C	Limestone	95
	◑	C	Limestone	96
	◐	C	Dolomite	58
	-○-	C	Aragonite	97
	⦶	C	Marl	88
Coutant, et al.[9]	□	C	Limestone	90
	■	R	Limestone	90
TVA[24]	▲	R	Limestone	90
This Study	●	C	Pelletized CaO	100
	○	C		
	◎	C		

FIGURE 7



COMPARISON OF SIMULATION RESULTS ON SO_2 REMOVAL WITH FIELD TEST DATA OF SHAWNEE STEAM PLANT (WEN)

III. Discussion

As a result of the combined efforts of the modeling activities and extensive experimental investigation, considerable progress has been made toward an understanding of the phenomena on which the limestone injection process is based. A thorough and objective evaluation of the complete data available reveals considerable consistency and agreement on the effects of each of the major process variables on the effectiveness for SO_2 removal. The summary outlined here has focused upon the most critical of these variables—those which directly bear upon the ultimate potential of the process for pollution control purposes.

The first fact that can be regarded as established is that mass transfer of SO_2 to particle surfaces does not limit the rate of SO_2 capture in dispersed systems. This has been shown by the calculations performed by Howard and Ishihara and independently confirmed by the correlation of measurements of the initial reaction rates measured under isothermal conditions in the laboratory. Further experimental proof is provided by the high sensitivity of the dispersed phase reaction to temperature as shown by the activation energies determined by Coutant and Ishihara, and the lack of any effect of stoichiometry upon CaO conversion, shown by Ishihara.

It follows from this fact that the ultimate limitation to SO_2 capture by injection of limestone into a boiler is associated with intraparticle effects—either diffusional or chemical. It is further established that the initial rate of SO_2 sorption, i.e., the highest possible rate achievable, is determined by the intrinsic chemical reaction rate of CaO with SO_2. The rate of decay of this high initial rate determining the efficiency of the process can be attributed to three possible causes: (1) formation of a product shell on the particle surface, (2) formation of product shell on individual CaO grains within the particles or (3) reduction in chemical reaction rate due to loss of surface area as a result of grain growth. The effect of the process variables on the anticipated rate are different in each case and comparison of models with the established characteristics of the reaction permits this question to be decisively answered.

In the summary of Pigford's model it was shown that severe discrepancies exist between the observed effects of temperature and particle size and the responses predicted by the model. The model is likewise in conflict with the effect of SO_2 concentration and the established activation energy of the isothermal reaction. Although the postulation of diffusional resistances as the rate limiting factor is intuitively appealing particularly for the final stage of reaction, it is not consistent with the observed characteristics of the reaction.

The assumption of a combination of diffusional and chemical resistances to be controlling, as exemplified by the MIT model, is also in serious conflict with experiment. The failure of the model to properly predict reaction profiles as determined by microprobe analysis, was later pointed up when Wen evaluated the diffusion modulus at 1/30 the value estimated by the MIT model. Likewise, the effective diffusivity was determined to be about 0.07 cm^2/sec. rather than the 0.2 cm^2/sec initially estimated by MIT. The variation of surface area with particle size was disproven by BET measurement and the predicted effect of temperature on surface area also failed: after calcination at high temperature, the surface area is independent of particle size or reaction temperature. In view of the fact that Wen's model also assumes diffusion to be a major resistance under certain conditions, and is entirely consistent with experiment one can only conclude that the MIT model contains mathematical errors, or that the equations have solutions that were not recognized.

The attached table summarizes the principal experimental results with which any useful model must be in substantial agreement. Each model discussed here is qualitatively compared with these results. Also included in this comparison are the predicted responses for pure shell diffusion, since this mechanism had long been regarded as the most probable limitation of the process. It is clear from this table that shell diffusion is inconsistent with nearly every one of the observed responses,* and need not be further considered.

The best general agreement with experiment is, of course, obtained with the empirical models. The Ishihara and Coutant models are combined for this comparison since it was shown that they are both representative of homogeneous chemical reaction, influenced by strong surface area effects. It is assumed in this comparison that the effects of time, temperature and particle size that have been established are taken into account when applying the model.

The Wen model is again the same homogeneous representation as that of Ishihara-Coutant, except that it specifically identifies the surface area with the CaO grains within the calcine particle. It therefore lends itself to quantitative treatment of the surface area effect independent of the other parameters and will ultimately be the most generally applicable form of the model for predictive purposes. The Wen model is the only form which can be applied to the complete range of homogeneous, zone and shell reactions for both isothermal and nonisothermal reaction conditions. The primary limitation in accuracy of the Wen model is that there is no way to predict grain size *a priori* from given process conditions. Thus, in applying his model to simulate the Shawnee boiler, a constant grain radius is assumed, i.e., surface area does not change with time and is independent of particle size or injection temperature. The data of Ishihara and Coutant clearly show that this assumption is not correct, but it does permit one to formulate a first approximation. As shown by Figure 5, this approximation is limited in accuracy to ± 30% of the observed efficiency. The predictive accuracy of Wen's model would no doubt be greatly improved if Ishihara's data on the effects of particle size and injection temperature were incorporated to account for changes in grain radius with residence time. This modification would probably also bring the model into agreement with the first order kinetics established for the isothermal reaction (fixed grain size).

The preponderence of evidence resulting from the work of Ishihara, Coutant and Wen overwhelmingly favors chemical reaction as the controlling mechanism of the process. This mechanism is the only one consistent with all of the facts, and the ultimate

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*Microprobe analysis of the cross sections of particles reacted in the Shawnee boiler[2 3] show homogeneous distributions of reaction product within particles smaller than about 40μ. Particles larger than 40u show distributions similar to those proposed by Wen for zone-type reactions.

Table III

Comparison of Model Predictions With Experimental Results

Experimental Results	Homog. chem reaction (Ishihara-Coutant)	Chem. react. shrink. grain core (Wen)	Pore diffusion-surface react. solid diff. (MIT)	Grain shell diffusion-pore diffusion (Pigford)	Product layer diffusion (Shell)
Particle size effect	√	√	×	×	×
Temperature effect	√	√	×	×	×
Surface area-initial rate	√	√	√	√	×
Surface area - particle size	√	×	×	×	×
Terminal Conversion - particle size	√	×	×	×	×
Isothermal reaction rates	√	√	√	√	×
SO_2 concentration	(a)	(a)	√	×	√
Act. energy-conversion	√	√	√	×	×
Isothermal reaction profiles	√	√	×	√	×
Nonisothermal reaction profile	√	√	×	√	×
Overburning - SO_2 reactivity	√	√	×	√	×
CaO content of lime	√	√	√	×	×
Sulfation effect	×	√	√	×	×
Conversion time profile	√	?	×	×	×
Total residence time		√			
Terminal conversion - total residence time					

(a) Expected to agree when model is modified to account for change in surface area with time.

self-limitation of SO_2 capture by the lime particles after injection necessarily follows from the known changes in surface area that occur with overburning. The low final rate, like the high initial rate, can indeed be calculated from the chemical reaction rate constant and surface area.

IV. **Conclusions**

The limestone injection process is limited by the rate of chemical reaction which is, in turn, limited by the rapid loss of surface area (due to grain growth) immediately following calcination.

This self-limiting aspect of the reaction necessarily defeats any attempt to improve performance by manipulation of process variables, e.g., particle size, injection temperature, particle/gas distribution.

The efficiency of SO_2 removed, within these limitations, can be successfully simulated by homogeneous reaction models, such as that of Wen. As a first approximation, assuming constant grain size, such a model will predict results within 30%. Improved accuracy must rely on empirical correlation of particle size and temperature effects. Data for such correlations are already available.

The limit of efficiency for the process, as determined from experiment, is 20 percent per stoichiometric injection.

Regardless of kinetic limitation, CaO utilization cannot exceed 50% due to physical limitations of the reaction.

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APPENDIX K

UTILIZATION OF LIMESTONE-MODIFIED FLY ASH

Although the utilization of limestone modified fly ash (hereafter as LMF) is not directly related to the dry limestone injection process and demonstration of optimum SO_2 removal, this section provides an overview of the activities in this area of the overall EPA program. Additional information may be found in the references.

Utilization of Limestone-Modified Fly Ash

I. Introduction and Objectives

The Dry Limestone Injection Process is a "throw-away" process and does not depend on the recovery of a salable chemical byproduct. Aware of the increased solid waste generated by the process and attempting to avoid aggravating one pollution problem while solving another, EPA initiated an extensive research effort in the early planning stage of the overall program. The objective of this part of the overall program was to determine and demonstrate the utilization of pulverized coal fly ash modified by limestone. A secondary consideration was the potential for reducing costs of the process through potential re-use of sorbent or byproduct credit.

II. Approach

The general approach taken was to determine current and potential utilization of unmodified fly ash, assess applicability of LMF to these utilizations and, based on its properties, assess its potential for new applications. Although there are a large number and variety of industries and individuals involved in the production and use of fly ash, the program was directed toward coal-burning power utilities, since this is the major source of fly ash in the U.S. The specific approach was to: (a) perform literature searches for utilization of unmodified and LMF; (b) correlate reported uses with analyses of chemical and physical properties; (c) prepare products by simulating current production processes as closely as possible; and (d) compare product properties and characteristics with their commercially available counterparts. Based on technical potential, economic analyses and more extensive utilization research were then performed or recommended for follow-on projects. Because of the relationship between the LMF from dry processes and wet scrubbing processes regarding waste disposal and beneficiation, samples for analysis and small scale product preparation were obtained from dry limestone injection programs conducted by TVA, Babcock and Wilcox, Chevrolet, and Detroit Edison, and from wet scrubbing programs conducted at Kansas Power and Light, Union Electric and Detroit Edison. Samples of normally produced fly ash were also obtained from these sources.

III. Results and Conclusions

A. Unmodified Fly Ash Utilization[1]

Although fly ash is used in various applications, current utilizations consume only a small portion of the total amount of fly ash available: of the 26.5 million tons of fly ash produced annually by coal-burning power plants, only about 1.6 to 2.0 million tons are utilized.

All known specifications for fly ash used as a material for product manufacture or application, and for fly ash products were examined for the purpose of assessing the extent

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to which they inhibit the utilization of fly ash. Except for the specifications on fly ash as an admixture in portland cement concrete, specifications do not inhibit the use of fly ash. The amount of fly ash that could be technically utilized in various applications used today, regardless of supply and economic factors, was estimated to identify those areas that would benefit most from the increased mass utilization of fly ash; this indicated where effort should be applied to improve the market. Maximum technically feasible uses of at least 1 million tons per year are listed in Table 1, column 1, based on ash composition and possible product utilization alone. The 1970 actual utilization values for each use, listed in column 2, total 1.6 million tons per year. As a result of this survey, it is estimated that if fly ash were used in the applications listed in Table 1 such that the maximum practical potential would be utilized under current technology and associated market conditions, approximately 7 million tons would be utilized, as shown in column 3. The significance of this list is that it indicates approximately 75 percent of the fly ash produced in the United States is not marketable without significant changes being made to reduce or eliminate the following limitations: (a) inadequate technology and knowledge dissemination related to known uses, (b) geographic limitations on transportation economics, (c) insufficient marketing efforts, (d) lack of control of fly ash production and supply, (e) cost effects of other materials or processes, and (f) insufficient development of new technologies.

The values in column 4 are estimates of the fly ash that would be consumed if all the limitations just cited were removed, except some geographic limitations on transportation. These values are estimates but they indicate areas where it is believed fly ash can be used in large quantities if appropriate steps are taken. This approach limits the area of concern to: fly ash concrete, lightweight aggregate, road base courses, control of mine subsidence and fires and, such new uses or developments as gas concrete building construction, ceramic products, and mineral recovery.

The following paragraphs discuss the uses shown in Table 1:

Structural Concrete

Fly ash is used in portland cement concrete for the improved properties it imparts to the concrete. Among these improvements are pumpability, compressive strength, long-term strength, workability, finishability, resistance to sulfates and alkali-aggregate reaction, and decreases in heat of hydration, drying shrinkage, particle segregation, bleeding, permeability, and leaching. These improvements are well-documented and have been demonstrated repeatedly in actual practice. The net effect is a stronger and more durable product which requires less cost to put in place and finish. For properly proportioned fly ash concrete, early strength, form removal periods, and curing requirements are not use inhibitions.

Principal inhibitions to the use of fly ash in concrete are the lack of a dependable supply of usable quality ash, and nonrecognition of the technological gains and potential improvements which would allow the use of various qualities (or classes) of fly ash and greater than 28-day design strength criteria.

Table 1
Estimated Fly Ash Utilization Potential
(Million Tons Per Year)

	1	2	3	4*
			Estimated Utilization Potential	
Use	Maximum Utilization Technically Feasible	1970 Utilization	Current Conditions	Improved Utilization
Fly Ash Concrete (Structural, Mass and Concrete Products)	10-15	0.54	3.5	6.0**
Lightweight Aggregate	13	0.21	0.5	>3.0***
Raw Material for Cement	13	0.16	0.25	****
Bricks	10	--	--	--
Filler in Bituminous Products	1-2	0.13	0.75	****
Base Stabilized for Roads	> Annual Production	0.11	0.3	>10.0
Agriculture and Land Reclamation	> Annual Production	--	--	--
Control of Mine Subsidence and Fires	> 1	0.01	0.75	>1.0
Structural Fill for Roads, Construction Sites, Land Reclamation, etc.	> Annual Production	0.32	0.6	****
Others (mineral, wool, gas, concrete, misc.)	--	0.16	0.25	*****
Total		1.64	6.9	--

*Values in Column 4 are scaled against the current market, but may take as much as 5 to 10 years for realization with maximum efforts.

**Value can be increased considerably with use of fly ash gas concrete in building construction.

***Has potential for accelerated future growth well beyond the proportions shown here.

****No appreciable increase.

*****Significant increases are possible through new developments such as ceramic products and mineral recovery.

The choice of concrete cure time should be based on the economics involved with construction. Since the cost impact on materials by using fly ash is often small relative to the cost of placing and finishing the concrete, the design conditions should be dependent upon the construction requirements. However, the state-of-the-art in concrete construction requires design compressive strengths of 28 days and does not include an optimal cure time in the total economics. A cure time of 28 days represents the point at which portland cement concrete attains up to 90 percent of its ultimate strength and is considered representative of the true strength of the concrete. However, in concrete containing fly ash, 28-day cure times are arbitrary and meaningless since the strength tested at that time does not represent the ultimate strength of the concrete when fully cured, which occurs after 28 days. Using a 90-day cure, for example, allows more fly ash and less cement provides higher strength, and affords advantages in pouring, pumping, and finishing. While the concept of 28-day design strengths largely dominates the concrete construction industry, there are few examples that can be cited in which structures under construction experience their design loads in 28 days. Until the concrete construction industry becomes aware of the increased latitude in concrete mix design that is offered by a technology using fly ash in an effective, economical manner, an inhibition to the use of fly ash in concrete will persist.

Significant deterrents to the massive use of fly ash in concrete, assuming an adequate supply and improved technology, are the requirements for additional storage and handling equipment at the ready-mix plants, and hauling costs. The economics of fly ash concrete related to the ready-mix operation was investigated to determine if storage, handling, and hauling costs are inhibitory factors since the literature is weak in this respect. The investigation could not include a detailed, comprehensive cost analysis within the scope of the project funds because of: (a) the numerous variables involved, plus the variation in costs from region to region; (b) the use or nonuse of beneficiation of the fly ash, brokerage fees, and financial assistance to ready-mix dealers for new equipment; and (c) sliding costs related to local competition. The analysis was therefore limited to estimates of the more significant factors, i.e., costs of fly ash F.O.B. utility, cement, truck hauling, new equipment, and chemical admixtures.

Strict conclusions cannot be drawn from this analysis because of the many cost variations involved for each case; however, indications are that a dealer can increase his profit before taxes by approximately 50 cents per cubic yard if high quality fly ash concrete is delivered within 10 miles of the fly ash source, or he can break-even at about 150 miles. On the other extreme, there is the possibility of a combination of circumstances, including the use of low-grade fly ash, which indicates that the user will not be able to match portland cement air-entrained concrete on an equal production economics basis. In most cases, however, the dealer should be able to produce fly ash concrete to compete with portland cement concrete for haul distances of approximately 50 to 150 miles, depending on the many cost factors involved. Since the profit, before taxes, on portland cement concrete is in the range of $2 to $3 per cubic yard (according to various personal contacts), a potential increase of 20 to 50 cents per cubic yard would be appreciable to the dealer. If circumstances, as noted above, increase the cost to the dealer, that increase is generally small enough to be absorbed by the contractor who stands to benefit from the economic and technical advantages of using fly ash concrete. Production costs of fly ash concrete can be reduced rather dramatically in consideration of the utilization of greater-than-28-day design strengths described earlier. Using this technology where applicable can reduce cost for any type of concrete, and for some, the reduction can be well in excess of one dollar per cubic yard.

Barge or rail transport provides a less expensive means of hauling fly ash than truck, but is applicable to only certain geographic situations. Since the development and acceptance of a standardized fly ash concrete technology by the concrete industry would expand the market and bring a large percentage of the power companies into the supply market, any transportation inhibition would be significantly decreased in most of the eastern half of the country.

In summary, current specifications on fly ash as an admixture in portland cement concrete inhibit the use of fly ash. There are individuals and organizations who, by combining the production or procurement of quality fly ash, appropriate concrete technology, and dissemination of the knowledge, have marketed fly ash readily within the limits of existing specifications (ASTM or Federal Bureau Specifications) or have written their own (e.g., TVA). Since the general fly ash user and producers have not done this the use of fly ash concrete is not widespread. The lack of understanding of fly ash concrete by the general public and isolated cases of fly ash misuse and the dissemination of inaccurate or misleading information concerning fly ash (e.g., broadcast of the term "waste product," intolerable low early strength, and bad color) have inhibited involvement by potential dealers, contractors, architects, and engineers. Power companies (with few exceptions) have not taken the initiative to improve the quality of fly ash or to maintain a consistent quality. Improvement in that area would undoubtedly relax the inhibitions to the use of fly ash by giving potential users the assurance of having a readily available supply of a quality grade of fly ash. It is believed that a considerable portion of the fly ash produced today is usable as an admixture in portland cement concrete.

The continued development and acceptance of properly proportioned fly ash in concrete is likely to provide the basis for renewed interest in fly ash as a concrete ingredient. Intensive sales campaigns, although beneficial, have been effective only locally. When concrete users become fully aware of the range of advantages and properties that properly proportioned fly ash concrete offers, their reluctance to use fly ash in concrete should diminish; this should create an increase in demand.

Mass Concrete and Concrete Products

Fly ash is used in much of the mass concrete construction (e.g., dams and spillways) undertaken by the U.S. Army Corps of Engineers and the Bureau of Reclamation.

Specifications exist for this use and fly ash is proportioned accordingly, principally to lower the heat of hydration and also for its pumpability feature. Technically, a larger percentage of fly ash could be used in these structures; however, the present proportioning is adequate. The bulk of this work is being performed in the western United States where fly ash must be transported for long distances, thus reducing economic incentive. Fly ash may become more economically desirable with construction of new coal-burning power stations opening in the West. Usage may increase but the small number of such projects makes this potential use a small percentage of the national fly ash supply.

Concrete products such as building blocks, pipe, and precast units represent a very attractive field for fly ash usage. Fly ash is used for this application and is well accepted; its principal drawbacks are the lack of guaranteed quality ash and transportation cost limits. If this industry were exploited to its fullest extent, it would consume an estimated maximum of 5 percent of fly ash production.

Lightweight Aggregate

The predicted high future demand for lightweight aggregate is based on dwindling supplies of natural aggregates plus the increasing recognition by architects and engineers of a future demand for large-scale usage of lightweight concrete. Present developments of fly ash lightweight aggregate production technology in the United States, Canada, and Germany were reviewed. All are still in various phases of development and are attempting to solve technical production problems. Lightweight fly ash aggregate in the U.S. is not yet considered to be economically competitive product.

This is a relatively undeveloped industry, and solutions to its problems are being sought and incorporated in the process. Although a quality product can be manufactured, whether the manufacturing process and market can be sufficiently developed to economically compete with other lightweight aggregates remains to be seen. A significant increase in the utilization of fly ash for this application appears possible, but not probable in the near future.

Portland Cement Manufacturing

Fly ash lends itself economically to the production of portland cement only under certain special situations where the manufacturing plant is not located adjacent to the major raw material source or where possibly the required mineral deposits are located close to a utility. However, in most cases such special situations do not exist. This, coupled with the fact that there is no need for new cement plants since the present market demands considerably less than production capacity, indicates that the potential for utilizing fly ash in large quantities for the manufacture of portland cement is relatively low.

Bricks

Although fly ash can technically be used for making bricks, there is no shortage of clay deposits for brick making. The principal sources of fly ash in the United States are all close to ample sources of natural raw materials for brick manufacturing. The coincidence of a depleting source of natural raw materials, a dependable local source of high quality fly ash, and a knowledgeable entrepreneur may determine whether fly ash will eventually find local application as a brick ingredient. Additional factors indicating that this utilization potential will not materialize appreciably include: (a) fly ash brick manufacturing requires new handling equipment and production machinery, (b) fly ash bricks are not significantly cheaper than ordinary bricks, and (c) the present United States brick production capacity exceeds demand.

Bituminous Filler

There are numerous uses for fly ash in bituminous products, however, its use as a mineral filler in asphalt concrete (black top) pavement is the major application for large tonnage usage. Low quality fly ash can be used and current technology is sufficient. The competition to fly ash includes an array of low cost, abundant materials, all of which are adequate as a mineral filler. Although this is a good use for fly ash, particularly considering the mileage of new asphalt roads (2 to 4 in. thick) or resurfacing of old roads (1 in. thick), the potential usage is not large, probably much less than 1 million tons per year. This limitation, caused by competition, is aggravated by the special problems of storage and handling.

Road Construction

Except for use as a mineral filler in asphalt or occasional use as a structural land fill, road base course applications appear to be the only practical large-scale use for fly ash in road building. Although this application has an extremely large potential—technology is developed and a technical superiority over competing materials has been demonstrated—certain inhibitions prevent its substantial growth. Fly ash is not widely used in road contracts even though its cost is less than or equal to competing materials of equal strength for urban construction. Proven applications are classified as lime-pozzolan-aggregate base courses (pozzolan base), which involve patent rights. Factual data which would substantiate the inhibition of the use of this material because of royalty payments were not found; however, such an excuse was occasionally given for nonuse.

The pozzolan base course is used mostly for urban applications. Portable mixers are not widely used, and hauling costs are often limited by the use of materials available at or near the construction site. However, the amount of paving urban roadways, subdivision streets, parking lots, and airports represents an extremely large market. Present usage appears to extend as far as 40 to 50 miles from the mixing plant. Almost any fly ash produced today is adequate for this application, and it can be stored outdoors during the winter months and, with minimal processing, can be used during the construction season.

Valid inhibitions to the use of pozzolan bases were not uncovered even after contacting more than two dozen state highway departments. Most states are aware of its benefits but have chosen not to use it. The reasons were almost always vague. The principal inhibition may be that most potential users have not had experience with it and are reluctant to make a change. A thorough, detailed marketing analysis of road construction would be required for the various regions of the country within range of potential pozzolan base course supplies to determine the justification and advisability of action by government road contracting agencies relating to the use of fly ash for this purpose.

Agriculture and Land Reclamation

Although this application appears to be a method for utilizing large amounts of fly ash, it is not economically attractive when compared to the use of lime or other additives to adjust soil pH. Transportation and handling costs appear to be prohibitive for the large amounts of fly ash that would be required. Generally, the ratio of fly ash to limestone required to achieve an equivalent soil condition or crop yield is sufficiently high (as much as 30 to 1) to be beyond consideration. Moreover, the presence of certain trace elements often found in fly ash would be detrimental to the growth of many common types of vegetation. Although it may be useful in certain local areas, it is not expected to be useful on a wide scale.

Remote Filling of Mine Cavities

Mine subsidence damage to homes, bridges, and roads is an increasing problem. The increase, due only partially to additional mining, can also be attributed to the growing need for urban and suburban land which has resulted in building over old mines; deterioration of supporting conditions results in surface subsidence many years after mining has occurred. In addition to the subsidence, fires have also become a serious problem in abandoned coal mines. The technology has been developed for remote filling of mines and the cost is estimated at $2.00 to $4.00 per ton within 30 miles of the source if the fly ash is provided free of charge by the utility. Since many large coal-burning power plants are located near coal mining areas, the filling of abandoned mines appears to be an excellent means for utilizing/disposing of the entire amount of fly ash produced by these utilities. Many utilities are currently incurring costs of up to $2.00 per ton to dump fly ash and as much as $4.00 per ton where local regulations require the utility to landscape the land fill area. This factor plus the economic considerations of land value improvement resulting from the elimination of mine subsidence could possibly justify the economics of this form of utilization, particularly when more profitable uses cannot be employed.

Land Fill

Where structural land fill is required and hauling distances are short, fly ash can often be used more economically than other fill materials and can provide technical advantages. Among these advantages are ease of handling and spreading, low compaction density, and shear strength that continues to increase with time (a consequence of pozzolanic reaction with residual lime content in the ash). Fly ash covered with soil provides excellent drainage for vegetation. Also, any grade of fly ash is adequate and does not have to be stored, handled, or hauled in an enclosed and dry condition. However, the use of fly ash for land fill (excluding fly ash disposal) is not widely applied in this country. It has demonstrated its usefulness in the United States in embankments and abutment backing in highway construction, but it is not widely used for these purposes because of the availability of natural fill materials. Except for such special circumstances as extremely high fill embankments for roadways built over weak subsoils or unavailability of local fill materials, little use of fly ash as a land fill is expected except for disposal purposes.

Mineral Wool

The use of fly ash as the raw material for mineral wool manufacture requires no deviation from the state-of-the-art commercial manufacture of mineral wool; there appear to be no technical inhibitions to the use of fly ash in this application.

However, inhibitions are apparent in the comparative economics of manufacture and in the likelihood of overcapacity in competition with current mineral wool and fiberglass insulation materials. To date, there is no market for fly ash mineral wool.

Gas Concrete

Gas concrete is a porous concrete building material. It is approximately one-fourth to one-third the density of ordinary concrete and utilizes fly ash up to 80 percent of the solid constituent weight. Gas concrete is made in patented European processes and, although widely used in many foreign countries, is not used in the United States.

European utilization of gas concrete proves to be a highly desirable form of building material from the standpoint of construction economy and structural qualities. It is used in at least 20 countries. It is used on a wide scale in Denmark. Gas concrete is used in West Germany in the construction of 80 percent of all new factory buildings. In Sweden, its use approaches 100 percent, and in the Philippine Islands, it is now being used for the construction of low-cost housing projects. In England, it is estimated in 1971, approximately 1 million tons of fly ash was consumed in gas concrete. Since fly ash improves the quality (higher strength per unit volume) of gas concrete, reduces capital and production costs, and is available in abundance in urban areas, it could conceivably find a large market throughout the United States as a constituent of gas concrete. Additionally, fly ash used for this purpose does not have to be fine quality; that it can be hauled and applied in a wet state simplifies handling.

The future of gas concrete in this country is not readily assessable. As a new technology, it would have to compete with numerous well-established building techniques using conventional materials. To establish fly ash concrete as a building construction material on a wide scale would require substantial technical and economic surveys, coupled with dissemination of the technology and proven results.

Miscellaneous and Potential New Uses

Such other uses as in foundries, grouting, pipe coating, and oil well cementing are considered to have a low potential for the consumption of large quantities of fly ash. A large potential exists for such possible new uses such as sewage filtration/soil supplement applications, ceramics and mineral recovery, none of which has been developed.

B. Limestone-Modified Fly Ash Utilization

Limestone injection and/or scrubbing processes for the control of sulfur oxides can increase the amount of fly ash produced by as much as 1-1/2 to 3 times. These processes, if widely used, could have an appreciable impact on the existing and potential unmodified fly ash market.

Dry collected (LMF) was analyzed as collected and also after separation by mineral dressing techniques such as sizing, specific gravity, magnetic, electrostatic, and surface chemical (flotation) properties. Results of the whole sample analysis indicated that levels of silica, alumina and iron oxide, the major constituents of normal fly ash, are decreased while the lime and magnesia content is greatly increased with dolomite injection and the lime content is greatly increased with limestone injections. Based on extensive physical separations attempting to concentrate usable minerals, and utilization tests on the whole and sized fractions of modified fly ash, feasibility of utilizing modified fly ash in the manufacture of salable products was evaluated. This effort resulted in the classification of a number of possible uses for the material into the following technically potential categories.[2,3]

1. High Potential
    a. Mineral wool
    b. Sulfur dioxide recovery
2. Medium Potential
    a. Acid mine drainage neutralization
    b. Concrete admixture
    c. Cement kiln raw material
    d. Soil stabilizer and amendment
3. Low Potential
    a. Mineral recovery
    b. Fluxing agent
    c. Lightweight aggregate
    d. Fired structural products
    e. Unreacted calcium recovery

Following this effort the chemical and physical properties of wet-collected LMF were analyzed in addition to more intensive analysis of dry-collected LMF. Chemical analyses were performed using wet chemical, atomic absorption and atomic emission spectroscopic methods; physical analyses, employed mineral dressing, microscopic and X-ray techniques. The main constituents of modified fly ash were found to be silicon, calcium (and magnesium if dolomite is used as the modifying stone), aluminum, iron and sulfur. Wet-collected modified ashes usually had a higher sulfur content than dry-collected ashes though the amount of sulfur present in the ash is determined not only by the efficiency of the sulfur removal system but also by the amount of sulfur found in the coal burned. The physical melting properties of modified fly ashes were quite similar and all ashes tested melted within a temperature range of 2150°-2300°F. This similarity of physical characteristics was substantiated by microscopic analysis. Predominant size fractions of almost all ashes tested were 325 x 400 or -400 mesh. Sieve analysis of the three ashes most often used showed little or no beneficiation of elements upon sieving. The possibility of substituting the modified fly ash for regular fly ash in some of the more prominent current utilizations and in a limited number of new applications was evaluated by small-scale production simulating, as closely as possible, commercial production processes. A comparison of properties and characteristics yielded the following categories of technical potential.[4,5] Specific results and conclusions are included for each high potential application. Additional data on these as well as details of low potential applications may be found in the references identified.

1. High Potential of Utilization

a. Mineral wool

A carbon-arc tilting furnace was used to melt a wide variety of modified fly ash samples and mineral wool was produced by pouring the molten material from the furnace in a thin stream and into a jet of 90 to 95 psig compressed air. The air imparted a shearing force to the molten mass, breaking the stream into small droplets which formed fibrous "tails." Any solid remnants of the original droplets are termed "shot." Characteristics of the mineral wool produced are shown in Table 2. All pouring temperatures are below those necessary for wool production from bottom ashes and current commercial raw materials.

A significant difference was observed in the production yields from the individual samples. A much higher yield was obtained from sample KPL, the only wet-collected limestone modified fly ash availble, than from the dolomite fly ash. The lowest yield was obtained from sample CM, dry-collected dolomite modified fly ash, in which the coal and dolomite were premixed upon entering the combustion area. In comparing the acid/base ratios (percent silica plus percent alumina)/(percent lime plus percent magnesia) sample KPL at 1.30 falls closest to the generally accepted mineral wool production range of 0.85 to 1.25. SLD and CI (1.87 and 1.58 respectively) had lower yields than KPL.

Although samples CM and CI were produced from the same coal and the same dolomite, a difference in their yields of mineral wool was noted, possibly due to the different methods of introducing the dolomite at the boiler. Sample CM was formed by

Table 2

Production Characteristics of Mineral Wool

Sample	Type	Acid Base Ratio	Pouring Temp. °F	Blowing Pressure psig	Yield	Comments
KPL	Wet Collected Limestone Modified	1.30	2700	92	High	Light brown, short fluffy fiber, very little shot
SLD	Wet Collected Dolomite Modified	1.87	2800	90	Moderate	Gray, some brittle fiber, moderate shot
CI	Dry Collected Dolomite, Injected	1.58	2700	93	Moderate	Gray, resilient fiber, moderate shot
CM	Dry Collected Dolomite, Mixed	1.52	2700	95	Low	Gray, fluffy fiber, heavy shot
CU	Unmodified	9.79	3000	95	None	No fiber formed

premixing the dolomite and coal before pulverization and entry into the boiler while sample CI was formed by injection of the dolomite above the flame envelope.

Unmodified ash sample CU was utilized as a control. As shown in Table 2, no fiber could be produced even at temperatures as high as 3000° F.

Quality tests performed in accordance with the Department of Commerce, Commodity Standards Division: Commercial Standard CS 131-146 yielded the results shown in Table 3. Loose shot was removed from the samples which included a commercial mineral wool for comparison.

Although high quality mineral wool (accompanied by sulfur regeneration)—equal to or better than commercial mineral wool—was produced from both dry-collected and wet-collected limestone-modified fly ash, there is no market potential for the product since it is being replaced by glass wool.

b. Calcium-silicate brick

Calcium-silicate (CS) bricks of superior quality (compressive strengths in excess of 7000 psi) were produced from limestone and dolomite modified fly ashes. Experimental work proceeded in three phases with pellets (1" diameter by 3/8" thickness) being made initially to determine basic composition mixtures, forming pressures and autoclaving conditions for each individual modified fly ash examined. Dry-collected modified ash, and wet-collected ash, were selected for the second phase of research—the production of 2" x 4" x 1-3/8" bench-scale brick. This phase of the research dealt primarily with such processing variables as forming pressure, mixing, humidity curing, etc. In the final phase, full size brick was produced using common commercial equipment to determine whether the process could actually be scaled up.

Data obtained from the pellet tests indicated that CS brick could be produced from modified fly ash. When using dry-collected modified fly ash, the brick mix consisted of 50 percent (on a dry basis) modified fly ash, 50 percent silica sand and approximately 20 percent water; when wet-collected modified fly ash was used, CS brick could be produced containing 50 percent (on a dry basis) modified fly ash, 39 percent sand and 11 percent calcium oxide. Using wet-collected KPL fly ash, the process involved a dewatering of the slurry to 34 percent water before mixing. Such a composition provides sufficient water for mixing and forming of the green brick.

In the final phase of the testing program, 2" x 4" x 8" full size brick samples were prepared using a hydraulic-toggle dry-press. The final products met or surpassed ASTM (73-51 and 73-67) specifications of 4500 psi compressive strengths and less than 1 percent shrinkage for grade SW, severe weathering, calcium-silicate brick. An average batch of brick made from dry-collected ash displayed characteristics of 4600 psi compressive strength, 20 percent absorption and no measurable shrinkage; wet-collected ash produced brick with an average 4500 psi compressive strength, 28 percent absorption and no measurable shrinkage.

High technical potential was demonstrated for calcium-silicate brick made from modified fly ash. Although this type of brick is used in Europe it has no current market in the United States.

Table 3

Quality Tests on Mineral Wool

Sample	Average Fiber Diameter	Attached Shot wt. %	Moisture Adsorption st. %	Odor Emissions	Fire Resistance	Corrosion Retardance
KPL	2.5μ	14.0	0.001	No Apparent Difference	Incombustible	Noncorrosive, no etching
SLD	3.0μ	32.0	0.00	No Apparent Difference	Incombustible	Noncorrosive, no etching
CI	5.6μ	34.0	0.00	No Apparent Difference	Incombustible	Noncorrosive, no etching
CM	5.4μ	36.0	0.00	No Apparent Difference	Incombustible	Noncorrosive, no etching
Commercial	8.4μ	N/A	0.00	No Apparent Difference	Incombustible	Minor Corrosion, no etching

c. Aerated (gas) concrete

Aerated or foamed cellular concrete is a lightweight structural material consisting of small noncommunicating gas cells entrained in a calcium-silicate matrix. It is produced by inducing gas bubbles within a cementitious paste normally composed of cement and/or lime and a fine grained siliceous material.

The bubbles of gas are produced by one of two general methods:

1. By the formation of gas by chemical reaction within the mix during the liquid or plastic stage, for example:

$$2Al + 3Ca(OH)_2 + 6H_2O \longrightarrow 3CaO \cdot Al_2O_3 \cdot 6H_2O + 3H_2\uparrow;$$

or

2. By introducing air from without, either by adding a preformed foam or by incorporating air by whipping.

When the first method is used, the hydrogen in the cells is replaced by air in a short time and no fire hazard exists. The gas-cement mixture is allowed to set in air and is then steam cured at high pressure. Aerated concrete made in Europe using normal coal fly ash as the siliceous component is high in strength and light in weight—their best products having compressive strengths of 200-800 psi for concrete with a density range of 30-45 lb/cu ft. Aerated concrete also exhibits advantageous thermal insulation and acoustic properties.

Aerated concrete was produced from dry-collected limestone modified fly ash using the technology employed by European manufacturers with one basic exception. Utilizing the "free" lime content in dry-collected modified ash, the addition of lime is not required—a significant cost reduction. Aluminum powder is used to generate gas bubbles and portland cement is added to provide strength.

Dry-collected limestone modified fly ash from the Shawnee Steam Plant at Paducah, Kentucky (TVA), was selected for the bench-scale production of aerated concrete because of its high reactive or "free" lime content and its large siliceous component. It was found that aerated concrete could be prepared from this ash without the use of any additional material except water and aluminum powder—the aerating agent. The cured concrete had a compressive strength of 400 psi at a density of approximately 50 lbs/ft^3. Portland cement was then added to the mix to increase the compressive strength of the product. The density increased to 56.3 lbs/ft^3 when using cement and the compressive strength was increased to more than 855 psi. The addition of portland cement also stabilized the aerated mix prior to autoclaving. This is a critical factor because setting must occur after aeration is completed and before the entrained bubbles collapse.

Although these early results indicated high technical potential worthy of additional research—comparable compressive strengths at somewhat higher densities—there is no current market for aerated concrete in the United States.

d. Formed concrete block

Research on calcium-silicate brick production showed that autoclaving increased calcium-silicate bond formation. As a result, the feasibility of using modified ash as the cementing agent for the production of concrete block was investigated.

The composition of the cement block was the same as for calcium-silicate brick with the exception that less dewatering was required. The composition consisted, on a dry basis, of 50 percent wet-collected modified fly ash, 39 percent silica sand (30 x 100 mesh) and 11 percent lime (95 percent CaO). Also, the material was poured into molds instead of pressed. No prior grinding or crushing of the modified ash raw material was required. The resulting poured concrete, which was similar to concrete block, had a bulk density of 90 lb/ft^3 as compared to 150 lbs/ft^3 for conventional concrete block and a compressive strength of approximately 900 psi as compared to 1000 psi for conventional block. Although addition of the necessary aggregate could raise the bulk density to 100 lb/ft^3, this would still be only 2/3 the bulk density of standard block. The blocks produced out of the autoclave were full strength, nonshrinking products which do not require the 3-4 weeks air curing time before sale as does the conventional concrete block. On this basis, storage requirements could be reduced. However, as in the case of calcium-silicate brick, implementaion would require new techniques of production such as dewatering and autoclaving. As a result, there is no current U.S. market for formed concrete material made from modified fly ash.

2. Low Potential of Utilization

a. Soil amendment

b. Ceramic materials

c. Recovery of SO_2 (thermal)

d. High-pressure alumina leaching

e. Flotation as a means of producing separate fractions

Techniques for dewatering the wet-collected limestone-modified fly ash were evaluated in a follow-on project with the following resultant classifications of technical potential.[5]

1. High Potential
   - a. Settling
   - b. Pressure filtration
   - c. Centrifugation
2. Medium Potential
   - a. Flocculants

Details of the results are currently unavailable, however, settling is considered the optimum technique based on both economical and technical considerations. Pressure filtration and centrifugation, while having high technical potential, are not expected to be economical because the large volumetric capacities required could result in large equipment multiples.

IV. Summary

Limestone-modified fly ash differs considerably, both chemically and physically, from unmodified ash and does not lend itself to direct substitution for regular ash, as it is used today. In addition, the chemical and physical properties of modified ash vary to a large degree based upon the sulfur and ash content of the coal and subsequent removals during flue gas treatment.

There are, however, potential uses for the modified ash: some, the same as for regular ash; others not yet developed. Such miscellaneous factors as quality variation, water content, sulfur (sulfite, sulfate, gypsum) content, pozzolanic properties, quantities available, trace element content and toxicity and unreacted lime content need to be thoroughly evaluated for specific applications before applicability can be finally assessed. Research and development programs are necessary to determine and subsequently demonstrate the technical and economic feasibility of utilizations of this material.

General areas of potential technical utilization include autoclave products, structural or land fill, bituminous filler, pozzolanic materials, cement manufacture, pressure-sintered products, gypsum products, and mineral recovery. Immediately promising areas are autoclave products (sulfur would not be released), gypsum products (LMF contains large amounts of gypsum), road base course material (it contains lime, has pozzolanic properties and the potential market is large), and sulfur recovery (although the economics are not promising, it could supplement a sintering process).

Since the modified ash cannot currently replace regular ash in its utilization, its immediate impact on the regular ash market would be negative. It is possible, however, that processes can be developed that would make it usable by the time it is produced in appreciable quantity.

V. Recommendations

Although not the main thrust of the current program, recommendations are presented for unmodified, as well as for modified fly ash, because use of the former would contribute to the economic solution of the solid waste problem. Additionally, its use is expected to precede (and pave the way for) the use of modified fly ash since the former is more familiar, well characterized, and in current abundance. Recommendations are presented for wet-collected limestone-modified fly ash since dry-collected limestone-modified fly ash is not expected to be nationally abundant because of the limited application of the dry limestone injection process. However, the dry process may be utilized in a particular geographic area or localities which would make the dry-collected modified material locally available. The properties and characteristics of the dry-collected material are not expected to be sufficiently different from the dewatered wet-collected material to preclude its use for certain applications.

All recommendations have been submitted for review to appropriate agencies; e.g. the Department of the Interior and the Department of Housing and Urban Development.

A. Unmodified Fly Ash

Existing inhibitions to the utilization of regular fly ash are of such magnitude that only a small percentage of the ash produced today is utilized. These restraints will continue to prevent an appreciable growth of the fly ash market unless appropriate research, development, and survey programs are carried out. These programs may reduce inhibitions that retard fly ash sale on a profitable basis.

Major areas of interest for new efforts are structural concrete, road base course materials, and such new products as gas concrete, ceramics, and mineral recovery. Sufficient effort is already being applied to the advancement of the fly ash lightweight aggregate technology. An effort should also be directed toward the extended use of fly ash as a mine void fill, particularly since it could be an interim measure until the efforts requiring more lead time are completed and put into practice.

The recommendations are:

1. Expeditiously develop a new set of specifications or a handbook for the use of fly ash in portland cement concrete which would provide a standard utilization to produce predictable results. This would include the application of various grades of fly ash (pertinent parameters such as residual carbon, fineness, and pozzolanic activity) to concrete usage and encompass cure times beyond 28 days. These documents could be modeled after TVA specifications G-2 and G-30. A testing program will be required to provide statistical data to support this program.
2. Conduct a marketing survey for various regions within the fly ash supply areas to determine the economic feasibility of fly ash gas concrete in various forms of building construction in the United States.
3. Conduct a technical and marketing survey in various regions of fly ash producing areas to determine the justification for an advisability of action by government road contracting agencies regarding the use of fly ash in the base course section of Federal, state, and local paving program contracts.
4. Investigate the possibility of recovering minerals from fly ash.
5. Evaluate the net economic effects of coal-washing or gasification on the fly ash market and on the cost of ash disposal.
6. Conduct a technical and economic survey relating to land reclamation and to the remote filling of mine voids for control of mine subsidence and fires. This would include the economics of fly ash usage and land reclamation values; and the effects of fly ash on ground waters. Consider the use of empty returning coal cars or a fly ash slurry for transportation.
7. Conduct research to develop or improve such fly ash uses as ceramic products, optimized fly ash gas concrete.

8. Conduct fundamental research to identify the intrinsic characteristics and properties of fly ash to provide the basis for subsequent research into new uses of fly ash. Although this has been performed in part at various organizations, results of complete characterization are not published.

B. Wet-Collected Limestone-Modified Fly Ash

Determining the potential use of modified ash depends on research and development programs and marketing surveys to establish the potential marketability of developed products in terms of public acceptance and ability to compete with other products, including those produced from regular fly ash. The following programs are recommended:

1. The most critical research need for wet-limestone-modified ash is the fundamental characterization of its chemical and physical properties. This characterization will provide the basis for the subsequent utilization and toxicology research recommendations.
2. Conduct research and development programs on potential mass uses of modified fly ash including filler material, autocalve products, pozzolanic materials, pressure-sintered products, and gypsum products. These programs should be broad enough to allow the possible emergence of uses not yet identified. These programs should also consider the mass usage of modified ash in situ and beneficiated in processes in which sulfur is not released and recovered.
3. Investigate the recovery of mineral ore from the modified fly ash.
4. Determine the physical state of toxic elements within the modified fly ash, the source of these elements (coal ash or limestone), the role of wet collection in preventing mass contamination via particulate and gaseous effluents, and potential hazards that may exist (particularly through leaching) in the ash disposal and utilization.
5. Conduct an economics survey of the phase of electric power production involving: the effects of fuel preparation and delivery, pollutant removal, residue disposal, and product credits. Examples of trade-offs which should be made include: (a) scrubbing of fly ash and gases resulting from the combustion of untreated coal, (b) scrubbing of fly ash and gases resulting from the combustion of cleaned coal, (c) gasification of coal, and (d) liquefaction of coal.
6. Conduct surveys to determine the potential for marketing recovered sulfur and products to be developed for the use of modified fly ash. Also, consider the development of products which are already partially developed; e.g., mineral aggregate and road base course materials.

VI. References

Reports identified by numbers prefixed "PB" are currently available prepaid from: National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151. Others will be available approximately one month after receipt by NTIS.

1. Aerospace Corporation Report No. TOR-0059(6781)-1. PB 209-480, Final Report on "Technical and Economic Factors Associated with Fly Ash Utilization," July 26, 1971, EPA Contract FO4701-70-C-0059.
2. Coal Research Bureau, West Virginia University, PB 185-802, Final Report on "Study of the Potential for Profitable Utilization of Pulverized Coal Fly Ash Modified by the Addition of Limestone - Dolomite SO_2 Removal Additives," April 1969, EPA Contract PH86-67-122.
3. Ibid., PB 196-779, Final Report on "Study of the Potential for Recovering Unreacted Lime from Limestone Modified Fly Ash by Agglomerate Flotation," May 1970, EPA Contract PH22-68-18.
4. Ibid., Final Report, "Pilot Scaleup of Processes to Demonstrate Utilization of Pulverized Coal Fly Ash Modified by the Addition of Limestone-Dolomite SO_2 Removal Additives," March 1972, EPA Contract CPA70-66. Submitted to NTIS December 11, 1972.
5. Ibid., Final Report Draft, "Technical and Economic Evaluation of Dewatering, Production of Structural Materials, and Recovery of Alumina from the Limestone-Modified Fly Ash Produced by a Limestone Wet Scrubbing Process," Final Report anticipated early 1973, EPA Contract EHSD71-11.

PROCESS ECONOMICS

I. Introduction

One of the primary goals of the EPA-TVA dry limestone injection test program is to better define the process economics for potential users. The economics given in the 1968 EPA-TVA conceptual design and cost study (12) of the process were based on limited background and performance data; therefore, refinement of the earlier cost estimates is highly desirable and is now possible using the results of the Shawnee test demonstration.

Investment requirements estimated in 1968 were based mostly on discussions with solids handling equipment suppliers with some guidance from the TVA Office of Engineering Design and Construction in Knoxville, Tennessee, plus the use of indirect cost and installation factors derived from actual projects and from published estimating material. At that time, the most desirable limestone particle size and point of injection were unknown, predrying was not deemed necessary, solids disposal was assumed to be simple with water quality unaffected, and the full effect of injected calcium material on dust removal efficiency of electrostatic precipitators was speculative. All of these requirements have been given careful attention and definition by the Shawnee test program.

One factor of concern in 1968, which calcium base material should be utilized, is no longer of major importance since dried limestone serves as well as calcined limestone (CaO) or hydrated lime [$Ca(OH)_2$], both of which are two to three times more expensive. In the earlier cost study, only a few limestone suppliers across the United States were contacted for price data. Since then, the M. W. Kellogg Company has completed for EPA a much more comprehensive survey (8) of limestone supply and price data, and the information is utilized in this process cost evaluation.

In the earlier operating cost estimates, utilities usages were calculated and capital charges were based on nonregulated economics; that is, no provisions were assumed for maintaining the utility's rate of return on investment for the additional investment. As a result, an impractical, low rate of capital charges was assessed. In addition, a chemical plant operating stream time (8,000 hrs/yr) was used instead of a power plant's historical declining load factor and effort was not made to predict the lifetime operating costs of the system.

In the evaluation to follow, the actual cost of the Shawnee injection system, improved definition of raw material costs and desired particle size of injection material, actual utilities usage rates, more realistic capital charges and operating periods, recent air pollution emission requirements, refined dust removal technology, and equipment estimates by a precipitator manufacturer permit a far more accurate cost appraisal than was possible in 1968. However, it should be recognized that the accuracy of the newer estimates can be affected greatly by the difficulty of retrofit to a power unit, labor costs in the particular unit location, the closeness to a limestone source, the need and convenience of additional disposal area for the waste solids produced, local air and water pollution regulations, and the moisture content of purchased stone.

At this stage of development, the major factors affecting process economics include (1) power unit size, (2) sulfur content of fuel, (3) stoichiometric rate of limestone injection, (4) particle size of injected limestone, (5) particulate removal requirements, (6) solids disposal needs, (7) raw material costs, (8) annual operating time, and (9) remaining life of the power unit. Items (1) through (3) are the most significant factors in establishing costs since they determine the amount of limestone to be processed and, therefore, the required capacity of the equipment. However, item (4), particle size of injected limestone, has some effect on absorption efficiency, thereby influencing design of the grinding system and affecting both investment and operating costs. Particulate removal requirements, item (5), are, in part, fixed by the level of injection and emission laws prevailing in the plant location. However, the investment and operating costs associated with particulate collection vary depending on existing collection facilities and the type of additional facilities installed. The method and costs for disposing solids may also differ for various power plant installations. Raw material costs, annual operating time, and remaining life of the power unit do not influence investment; however, these items directly influence operating costs.

II. Approach

To evaluate the major factors, a variety of unit sizes, fuel sulfur levels, and limestone injection stoichiometries are chosen for case projections of fixed investment requirements, annual operating costs, and lifetime operating costs. Using selected cases, other key factors are also varied to analyze their sensitivity on process economics. The projections made are based on applicable design premises resulting from the Shawnee test program, plus the actual cost of the test facility and the actual utilities usage rates. A flow diagram of the proposed process and detailed material balances were prepared to serve as guides in determining equipment sizes and requirements for the various cases. Operating experience for TVA coal-fired power units is also utilized in the evaluation technique. For convenience, all projections are based on 1972 costs for the midwestern United States.

Results of the Shawnee tests indicate that, within limits, SO_2 removal efficiencies increase with the addition of greater amounts of limestone to the boiler. However, the associated costs and operating difficulties also increase. To determine the effect of limestone addition rate on process economics, a 52-case parametric study is used to cover the various unit sizes, sulfur levels, and injection stoichiometries. Cases were selected to expand the applicability of the Shawnee results over a broad range. Table 1 gives a detailed accounting of the chosen case combinations.

Design Premises—For the 52 cases, applicable design premises were established for the power unit, fuel, absorbent, combustion, reactions, SO_2 emission reduction, reaction products, and particulate collection and disposal method. A detailed listing of these premises follows:

A. Power unit

1. Size - 50, 150, 250, or 350 MW.
2. Location - midwestern region.
3. Type plant - existing, pulverized coal, frontal-fired unit.
4. Years remaining life - 15.

Table 1 - Dry Limestone Injection Case Combinations
Existing Coal-Fired Units

Injection stoichiometry, moles CaO injected per mole sulfur in coal		
0.8% S in coal	3.0% S in coal	5.0% S in coal
50 MW power units		
3.0	1.0	1.0
4.0	2.0	2.0
5.0	3.0	3.0
6.0	4.0	4.0
7.0		
150 MW power units		
3.0	1.0	1.0
4.0	2.0	2.0
5.0	3.0	3.0
6.0	4.0	4.0
7.0		
250 MW power units		
3.0	1.0	1.0
4.0	2.0	2.0
5.0	3.0	3.0
6.0	4.0	4.0
7.0		
350 MW power units		
3.0	1.0	1.0
4.0	2.0	2.0
5.0	3.0	3.0
6.0	4.0	4.0
7.0		

B. Coal

1. Heat value - 12,000 BTU/lb.
2. Ash content - 16.0%.
3. Sulfur content - 0.8, 3.0, and 5.0%.

C. Limestone characteristics and preparation

1. Type - calcite.
2. Composition - 95.0% $CaCO_3$ and 5.0% impurities (dry basis).
3. Purchased moisture content - 5.0% H_2O.
4. Purchased size - minus 1-1/2 in.
5. Moisture reduction - dried to approximately 0.5% H_2O prior to grinding.
6. Drying source - off-gas from combustion of No. 2 fuel oil with 20% excess air.
7. Size reduction - dry ground to 80% minus 400 mesh prior to injection.

8. Transport air:limestone injection ratio - 1:10.
9. Injection stoichiometry variations -
   0.8% S coal, 3.0 to 7.0 moles CaO: mole S in fuel.
   3.0 and 5.0% S coal, 1.0 to 4.0 moles CaO: mole S in fuel.

D. Combustion

1. Coal consumption prior to dry limestone injection - 0.780 lbs/kWh.
2. Excess air to boiler for combustion of coal - 25%.
3. Air inleak at air preheater - 13%.
4. Particulate emission - 75% of ash is emitted as particulates and is present in the off-gas.
5. Sulfur emission - 92% of sulfur is emitted as SO_2; remainder is chemically bound with the ash.

E. Boiler reactions, SO_2 emission reductions, and reaction products

1. Dried $CaCO_3$ decomposes to CaO and CO_2 within boiler.
2. Heat required for decomposition is supplied by combustion of additional coal.
3. For 0.8% S fuel, 5% of SO_2 in the gas combines with CaO per unit of stoichiometric limestone injected.
4. For 3.0 and 5.0% S fuel, 10% of SO_2 in the gas combines with CaO per unit of stoichiometric limestone injected.
5. All $CaSO_3$ formed by reaction of CaO and SO_2 is oxidized to $CaSO_4$ within the boiler.
6. All of the solid products resulting from limestone injection are present in the boiler off-gas as particulates.

F. Particulate collection

One of the drawbacks of dry limestone injection is the introduction of additional solids into the boiler, which requires additional particulate collection and disposal facilities. Figure 1 shows the effect of injection stoichiometry on the inlet particulate loading to the dust collectors for the three levels of sulfur evaluated. Design of the particulate collection facilities is based on the following premises:

1. Existing particulate collection facilities - mechanical collector followed by electrostatic precipitator.
2. Overall particulate collection efficiency of existing facilities - 99%, equivalent to a particulate emission of 0.03 grains/acf.
3. Additional electrostatic precipitator capacity is installed to maintain a dust emission level after dry limestone injection equivalent to the emission level prior to injection.

Reflecting the limestone injection case variations, Table 2 shows the calculated particulate rates at the entrance to the dust collectors for a 150 MW unit, and the overall collection efficiency required to maintain the base emission level defined above. These collection efficiencies are shown graphically in Figure 2.

G. Particulate disposal

Additional disposal facilities for handling the incremental solids are provided for each installation. Figures 3, 4, and 5 indicate the incremental disposal requirements

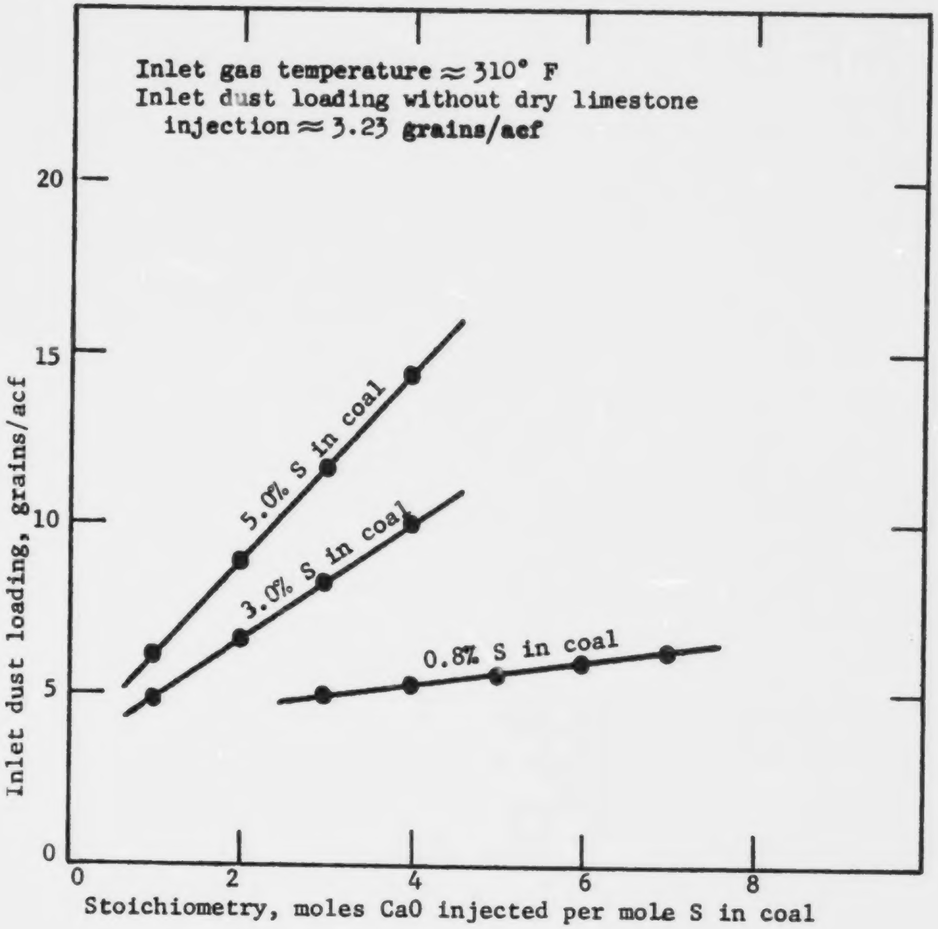

Figure 1. Inlet Dust Loading to Dust Collector System Using Dry Limestone Injection Process
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Table 2

Dust Removal Requirements for Dry Limestone Injection Case Study - 150 MW Plant (To Maintain Base Emission Level)

Case	Sulfur content of coal, %	Injection stoichiometry, moles CaO/mole S in fuel	Inlet to dust collector				Allowable emission, lbs/hr[a]	Overall dust collection efficiency required, %	Outlet dust loading grains/acf
				Dust rate, lbs/hr					
			Gas rate, acfm @ 310° F.	Fly ash	Injection products	Dust loading, grains/acf			
0	3.0	no dry limestone injection	507,700	14,040	-	3.23	140	99.00	.03
1	0.8	3.0	503,800	14,100	5,740	4.59	141	99.29	.03
2	0.8	4.0	505,200	14,120	7,660	5.03	141	99.35	.03
3	0.8	5.0	506,900	14,150	9,590	5.46	141	99.41	.03
4	0.8	6.0	508,100	14,160	11,530	5.90	142	99.45	.03
5	0.8	7.0	509,600	14,180	13,480	6.33	142	99.49	.03
6	3.0	1.0	512,500	14,100	7,580	4.94	141	99.35	.03
7	3.0	2.0	517,800	14,180	15,240	6.63	142	99.52	.03
8	3.0	3.0	522,700	14,240	22,990	8.31	142	99.62	.03
9	3.0	4.0	528,000	14,310	30,810	9.97	143	99.68	.03
10	5.0	1.0	519,000	14,150	12,670	6.03	141	99.47	.03
11	5.0	2.0	527,900	14,270	25,580	8.81	143	99.64	.03
12	5.0	3.0	537,000	14,390	38,750	11.55	144	99.73	.03
13	5.0	4.0	547,000	14,540	52,250	14.25	145	99.78	.03

[a] Equivalent to 99% removal of fly ash emitted from combustion of coal containing 16% ash

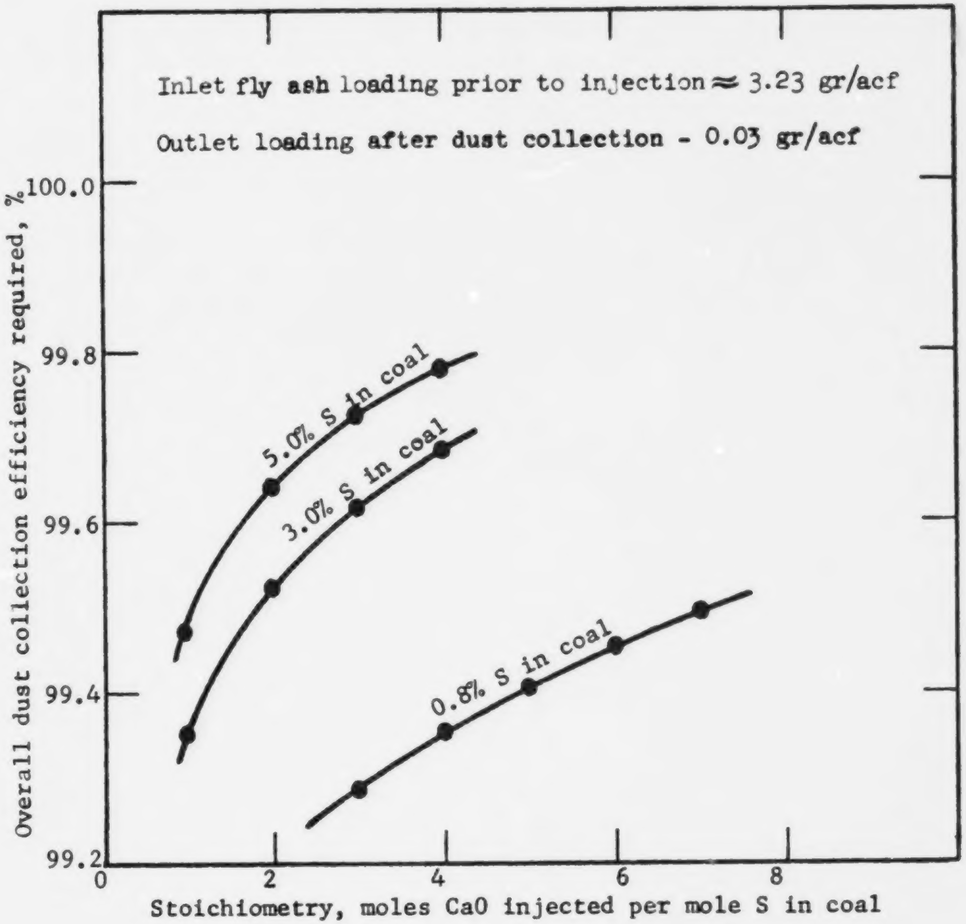

Figure 2. Effect of Injection Stoichiometry on Overall Dust Collection Efficiency to Maintain Emission Rate Equivalent to 99% Fly Ash Collection Prior to Dry Limestone Injection

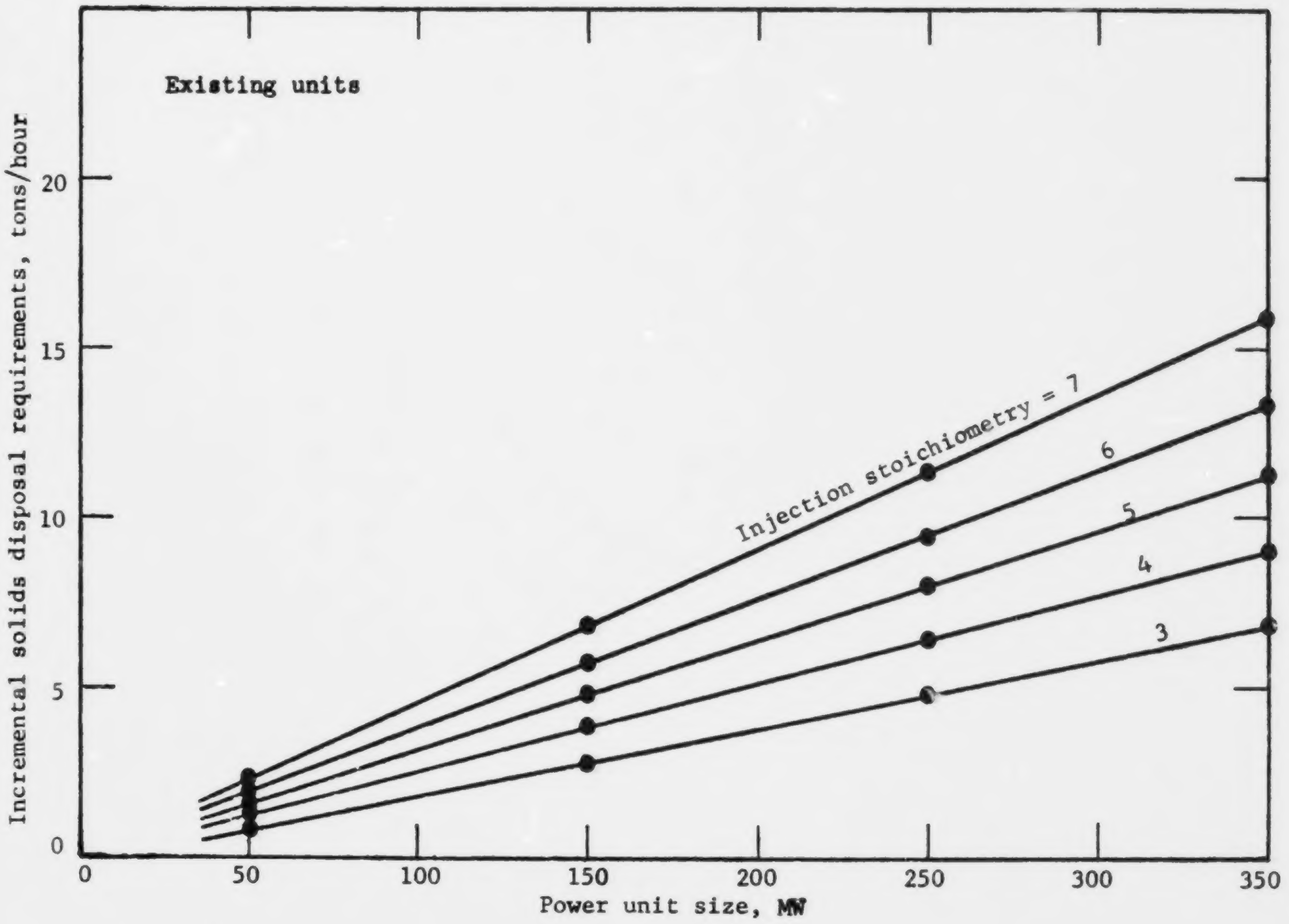

Figure 3. Incremental Solids Disposal Requirements for Power Units Utilizing **Dry Limestone Injection Process: 0.8% S Coal**

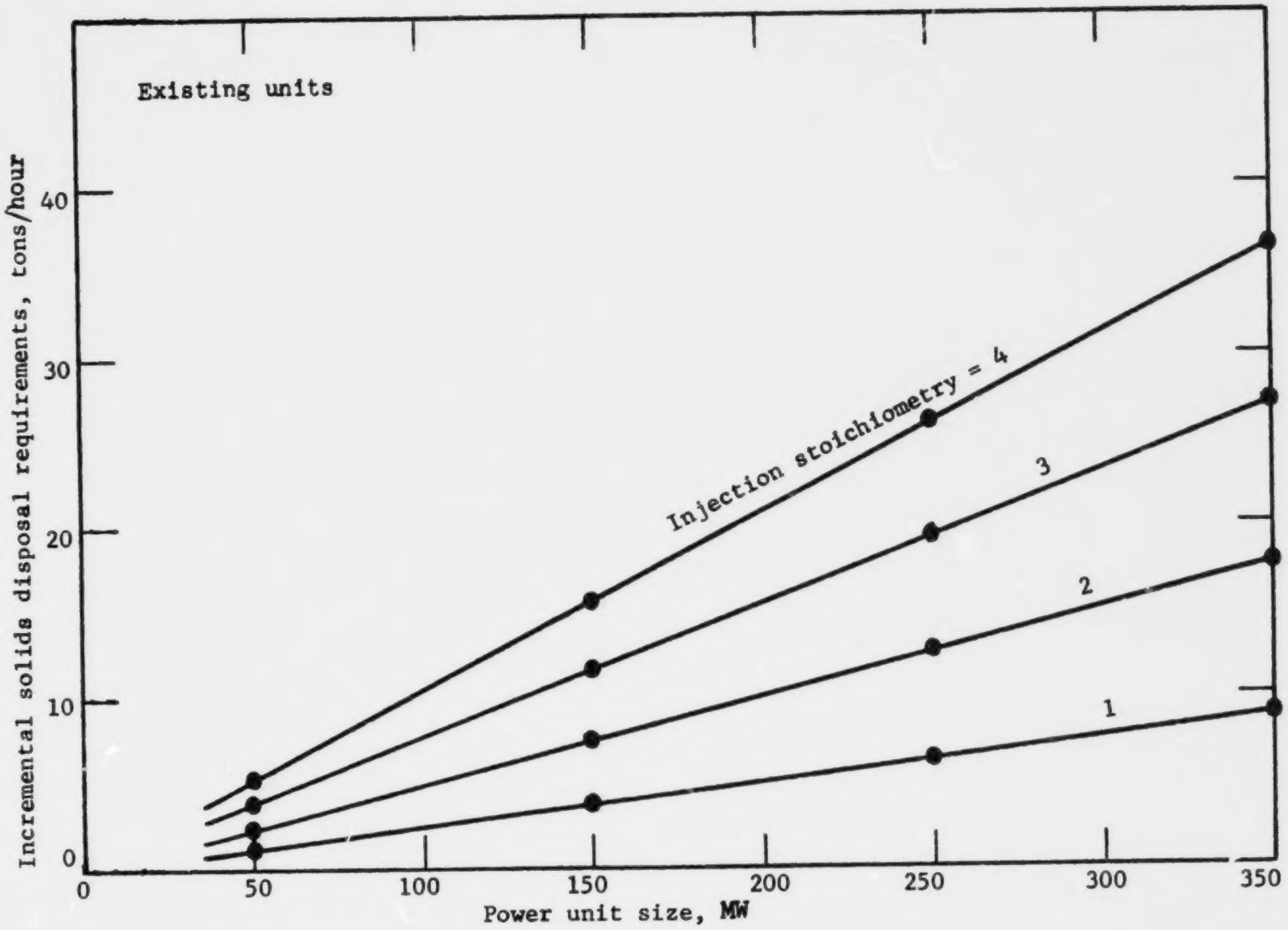

Figure 4. Incremental Solids Disposal Requirements for Power Units Utilizing Dry Limestone Injection Process: 3.0% S Coal

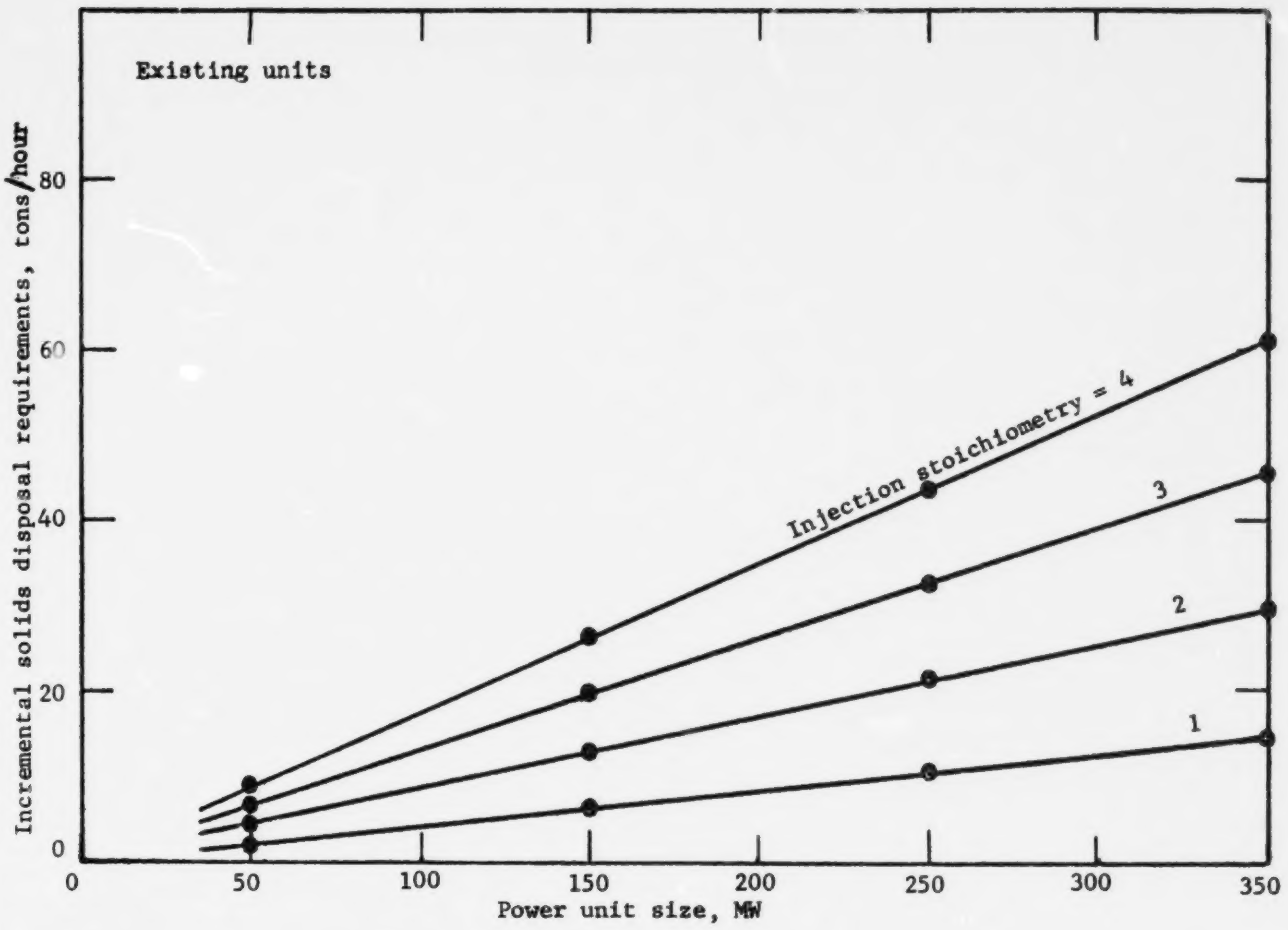

Figure 5. Incremental Solids Disposal Requirements for Power Units Utilizing **Dry Limestone Injection Process: 5.0% S Coal**

attributable to dry limestone injection for each variation in sulfur content as a function of power unit size and injection stoichiometry. The following method for disposal is used (11):

1. Fly ash and injection solids are disposed on-site in a common, existing settling pond. Additional pond facilities are not provided for the incremental injection solids.
2. Distribution facilities are included for supplying raw water to the solids disposal area. Pipeline distance between the disposal area and the raw water supply point is estimated as 2,500 ft.
3. Slurry concentration to the disposal pond is designed not to exceed 15% solids.
4. Fresh sluice water is used for disposing the incremental solids, with no provisions for recycling. Pipeline distance between disposal pond and the solids collection facilities is estimated as 6,000 ft.
5. A separate disposal line is included for each case, regardless of the magnitude of the incremental solids disposal burden.
6. Based on vendor recommendations, an 8 in. line is the smallest size which is practical. Disposal systems are sized with either 8, 10, or 12 in. lines, with a design fluid velocity of approximately 6 ft/sec and capability of disposing the daily load of solids over a period of 12 hrs. Based on TVA operating experience, the load factor for an existing ash sluice line is about 40% or less.
7. Spare incremental solids disposal lines are not provided. It is assumed that the existing spare sluice lines or the existing operating lines (with relatively low load factors) can be utilized as spares when required.
8. Based on TVA sluicing practices, sluice water flow through each operating line is continuous while the power unit is in operation (sluice water and electrical requirements for pumping are based on continuous flow.)

Using the Shawnee design and operating experience and the design premises presented above, a projected process flow diagram including provision for dust collection and disposal was prepared. This flow diagram identifies the major equipment required for the process and is presented in Figure 6.

Base Case—For convenience in preparing material and energy balances, a separate base case for each level of sulfur in coal was established. Power unit size was selected to conform to that of Shawnee Unit 10. Injection stoichiometry for each case was based on the most probable applications as determined in the Shawnee tests for the various levels of sulfur in coal. These case combinations are shown below:

Dry Limestone Injection Process Base Case Combinations

Power unit size, MW	Sulfur in coal, %	Injection stoichiometry, moles CaO injected/ mole S in coal
150	0.8	5.0
150	3.0	2.0
150	5.0	2.0

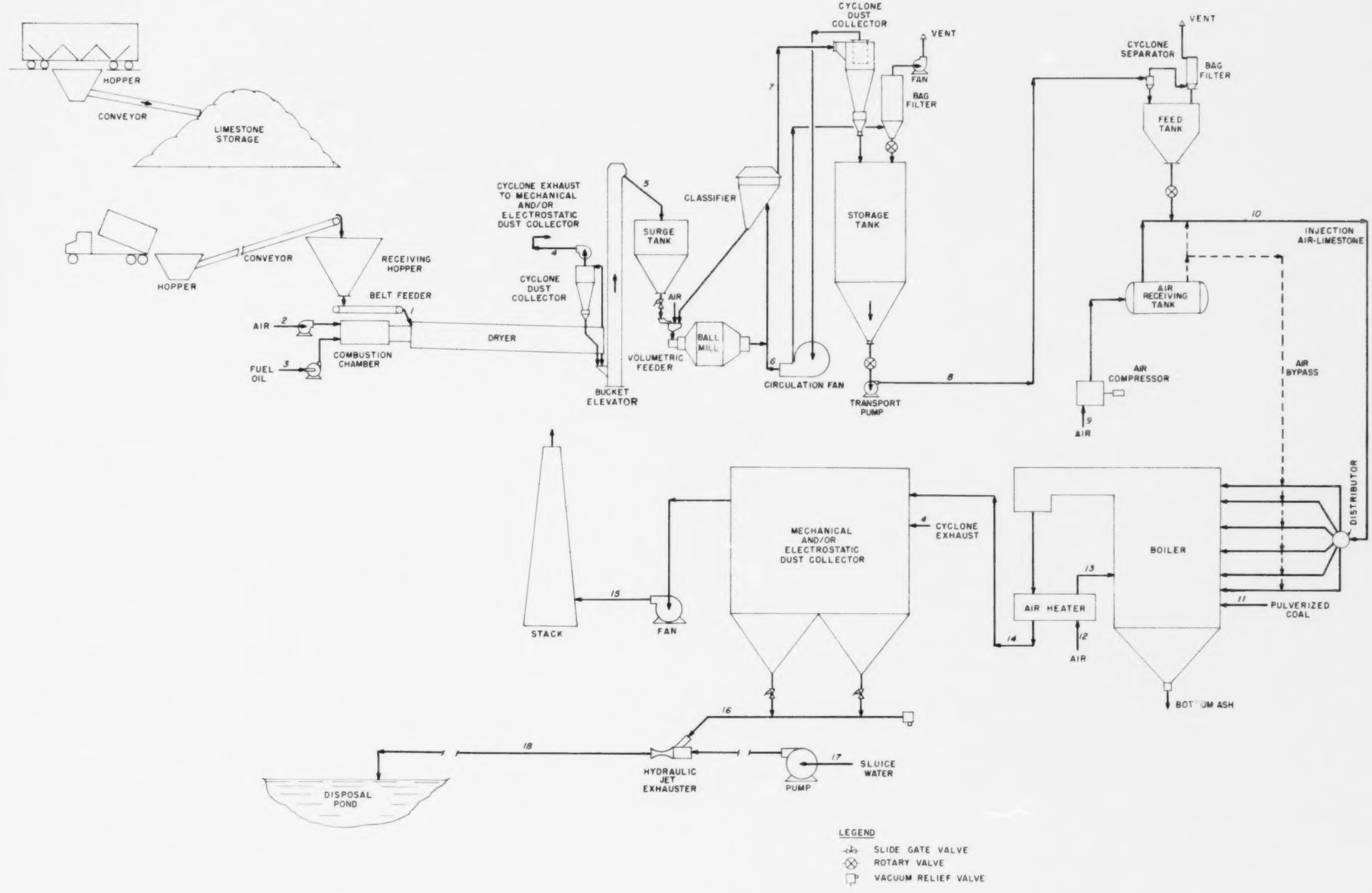
HOPPER
CONVEYOR
LIMESTONE STORAGE
CONVEYOR
HOPPER
RECEIVING HOPPER
BELT FEEDER
AIR
2
FUEL OIL
3
COMBUSTION CHAMBER
1
DRYER
CYCLONE EXHAUST TO MECHANICAL AND/OR ELECTROSTATIC DUST COLLECTOR
4
CYCLONE DUST COLLECTOR
BUCKET ELEVATOR
5
SURGE TANK
AIR
VOLUMETRIC FEEDER
BALL MILL
CLASSIFIER
6
CIRCULATION FAN
7
CYCLONE DUST COLLECTOR
VENT
FAN
BAG FILTER
STORAGE TANK
TRANSPORT PUMP
8
VENT
CYCLONE SEPARATOR
BAG FILTER
FEED TANK
10
INJECTION AIR-LIMESTONE
AIR RECEIVING TANK
AIR BYPASS
AIR COMPRESSOR
9
AIR
DISTRIBUTOR
BOILER
11
PULVERIZED COAL
13
AIR HEATER
12
AIR
14
BOTTOM ASH
MECHANICAL AND/OR ELECTROSTATIC DUST COLLECTOR
4
CYCLONE EXHAUST
STACK
15
FAN
16
18
DISPOSAL POND
HYDRAULIC JET EXHAUSTER
PUMP
17
SLUICE WATER
LEGEND
SLIDE GATE VALVE
ROTARY VALVE
VACUUM RELIEF VALVE

Figure 6 - Proposed Flow Diagram of Dry Limestone Injection Process

A detailed material balance for each of the base case combinations is shown in Figure 7.

Actual investment—The actual fixed investment for the Shawnee test facilities was analyzed to provide an equipment, labor, and material cost breakdown for the major process functions. The results are presented in Table 3 (1). A nine-month construction period during 1969-1970 and a total investment cost of $1,477,581 were required for the test facilities.

The facilities were designed with a 20 ton/hr injection capability equivalent to a 350 MW plant burning 2.0% S coal with an injection stoichiometry of 2.0. Although oversized for a 150 MW plant, a broad capacity range was necessary because of the research and development nature of the installation. The actual investment requirements discussed above include facilities for receiving, storing, drying, grinding, and injection and sampling test probes for the boiler. Both rail and truck unloading equipment are included. Boiler modifications such as wall port openings are included along with utilities distribution from the powerhouse area. Not included are capability for continuous fine grinding, additional particulate removal facilities, and solids disposal pond for the incremental dust burden. Also not included are additional soot blowers for removal of deposits which tend to form in the convection passes of the boiler. The number of required sootblowers may vary for different installations as a function of boiler tube spacing, temperature regime, and length of convection pass; however, each is estimated to cost $20-30,000. Since the Shawnee tests did not indicate the actual number of additional sootblowers required as a result of dry limestone injection, additional costs are excluded from the investment projections; however, the sensitivity of total investment as a function of sootblower requirements is discussed in Section II.

Investment projections—Based on the dry limestone injection process flow diagram, the process equipment was subdivided into several areas according to function. For most process areas, actual 1969 investment costs for the test facilities were updated to 1972 utilizing a Chemical Engineering plant cost index ratio of 138/119 (4). Instead of treating as separate areas, costs for painting, stairways, handrails, inspection, and testing were distributed to the appropriate major areas. For the limestone grinding system, updated costs were obtained from vendors to reflect the capability for continuous fine grind, not available with the Shawnee facilities.

Costs for facilities at other limestone capacities were projected by scaling the updated investment according to limestone throughput using appropriate scaling exponents. Values of these exponents were factored from the literature (6, 9) and from cost quotations obtained from vendors. Table 4 shows the major equipment areas which were established, the base 1972 investment corresponding to the updated Shawnee costs, and the scaling exponent used for projecting costs as a function of capacity ratios.

Costs for the incremental electrostatic precipitator and solids disposal systems were not scaled according to limestone throughput. Incremental electrostatic precipitator system

150 MW UNIT, 0.8% S IN COAL, 5.0 CaO:S INJECTION STOICHIOMETRY

STREAM NO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
DESCRIPTION	LIMESTONE TO DRYER	AIR TO DRYER	FUEL OIL TO DRYER	CYCLONE EXHAUST TO DUST COLLECTOR	DRIED LIMESTONE TO SURGE TANK	CIRCULATION AIR TO CONVEYOR	CONVEYING AIR TO CYCLONE	PULVERIZED LIMESTONE TO FEED TANK	AIR TO COMPRESSOR	LIMESTONE-AIR TO DISTRIBUTOR	PULVERIZED COAL TO BOILER	COMBUSTION AIR TO AIR HEATER	COMBUSTION AIR TO BOILER	FLUE GAS TO DUST COLLECTOR	FLUE GAS TO STACK	SOLIDS TO SLUICE EQUIPMENT	SLUICE WATER	SLURRY TO DISPOSAL POND
RATE, LBS/HR	16,360	5,490	310	6,540	15,600	40,400	40,400	15,600	1,500	1,500	117,880	1,479,860	1,340,500	1,586,400	1,592,940	23,599	133,701	157,300
SCFM	–	1,200	–	1,530	–	8,800	8,800	–	330	330	–	322,000	292,000	340,000	341,530	–	–	–
GPM	–	–	7	–	–	–	–	–	–	–	–	–	–	–	–	–	267	286
PARTICULATES, LBS/HR	–	–	–	20	–	2,750	16,350	–	–	15,600	–	–	–	23,720	141	–	–	–
TEMPERATURE, °F	AMBIENT	AMBIENT	AMBIENT	250	250	200	200	200	AMBIENT	110	AMBIENT	110	610	310	310	310	AMBIENT	AMBIENT
SPECIFIC GRAVITY	2.7		.865															1.10
UNDISSOLVED SOLIDS, %																		15

COAL ANALYSIS, % BY WT (AS FIRED BASIS)

H........4.17 ASH....16.00
N........1.23 H_2O.....9.70
C......66.39 O........1.71
S....... 0.80

COAL CONSUMPTION, .786 LBS/KWH WITH INJECTION
25% OVERALL SO_2 REMOVAL FROM GAS (5%/UNIT STOICHIOMETRY)
PARTICULATE COLLECTION EFFICIENCY, 99.41%

ESTIMATED COMPOSITION OF GAS TO STACK EXCLUDING NO_x, % BY VOLUME

CO_2	SO_2	O_2	N_2	H_2O	TOTAL
12.36	.04	5.43	74.35	7.82	100.00

150 MW UNIT, 3.0% S IN COAL, 2.0 CaO: S INJECTION STOICHIOMETRY

STREAM NO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
DESCRIPTION	LIMESTONE TO DRYER	AIR TO DRYER	FUEL OIL TO DRYER	CYCLONE EXHAUST TO DUST COLLECTOR	DRIED LIMESTONE TO SURGE TANK	CIRCULATION AIR TO CONVEYOR	CONVEYING AIR TO CYCLONE	PULVERIZED LIMESTONE TO FEED TANK	AIR TO COMPRESSOR	LIMESTONE-AIR TO DISTRIBUTOR	PULVERIZED COAL TO BOILER	COMBUSTION AIR TO AIR HEATER	COMBUSTION AIR TO BOILER	FLUE GAS TO DUST COLLECTOR	FLUE GAS TO STACK	SOLIDS TO SLUICE EQUIPMENT	SLUICE WATER	SLURRY TO DISPOSAL POND
RATE, LBS/HR	24,600	8,260	470	9,850	23,450	60,600	60,600	23,450	2,300	2,300	118,130	1,509,640	1,367,400	1,619,400	1,629,250	29,278	165,922	195,200
SCFM	–	1,800	–	2,300	–	13,200	13,200	–	500	500	–	329,000	298,000	347,000	349,300	–	–	–
GPM	–	–	1.1	–	–	–	–	–	–	–	–	–	–	–	–	–	332	355
PARTICULATES, LBS/HR	–	–	–	30	–	4,140	27,590	–	–	23,450	–	–	–	29,390	142	–	–	–
TEMPERATURE, °F	AMBIENT	AMBIENT	AMBIENT	250	250	200	200	200	AMBIENT	110	AMBIENT	110	610	310	310	310	AMBIENT	AMBIENT
SPECIFIC GRAVITY	2.7		.865															1.10
UNDISSOLVED SOLIDS, %																		15

COAL ANALYSIS, % BY WT (AS FIRED BASIS)

H........4.17 ASH....16.00
N........1.23 H_2O....9.21
C......66.39 O....... —
S........3.00

COAL CONSUMPTION, .788 LBS/KWH WITH INJECTION
20% OVERALL SO_2 REMOVAL FROM GAS (10%/UNIT STOICHIOMETRY)
PARTICULATE COLLECTION EFFICIENCY, 99.52%

ESTIMATED COMPOSITION OF GAS TO STACK EXCLUDING NO_x, % BY VOLUME

CO_2	SO_2	O_2	N_2	H_2O	TOTAL
12.28	.15	5.42	74.44	7.71	100.00

150 MW UNIT, 5.0% S IN COAL, 2.0 CaO: S INJECTION STOICHIOMETRY

STREAM NO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
DESCRIPTION	LIMESTONE TO DRYER	AIR TO DRYER	FUEL OIL TO DRYER	CYCLONE EXHAUST TO DUST COLLECTOR	DRIED LIMESTONE TO SURGE TANK	CIRCULATION AIR TO CONVEYOR	CONVEYING AIR TO CYCLONE	PULVERIZED LIMESTONE TO FEED TANK	AIR TO COMPRESSOR	LIMESTONE-AIR TO DISTRIBUTOR	PULVERIZED COAL TO BOILER	COMBUSTION AIR TO AIR HEATER	COMBUSTION AIR TO BOILER	FLUE GAS TO DUST COLLECTOR	FLUE GAS TO STACK	SOLIDS TO SLUICE EQUIPMENT	SLUICE WATER	SLURRY TO DISPOSAL POND
RATE, LBS/HR	41,290	13,860	790	16,520	39,370	101,500	101,500	39,370	3,900	3,900	118,900	1,531,590	1,387,300	1,649,200	1,665,720	39,707	224,993	264,700
SCFM	–	3,020	–	3,860	–	22,100	22,100	–	850	850	–	334,000	302,500	352,000	355,800	–	–	–
GPM	–	–	1.8	–	–	–	–	–	–	–	–	–	–	–	–	–	450	481
PARTICULATES, LBS./HR	–	–	–	50	–	6,950	46,320	–	–	39,370	–	–	–	39,800	143	–	–	
TEMPERATURE, °F	AMBIENT	AMBIENT	AMBIENT	250	250	200	200	200	AMBIENT	110	AMBIENT	110	610	310	310	310	AMBIENT	AMBIENT
SPECIFIC GRAVITY	2.7		.865															1.10
UNDISSOLVED SOLIDS, %																		15

COAL ANALYSIS, % BY WT (AS FIRED BASIS)

H.........4.17 ASH....16.00
N.........1.23 H_2O.....7.21
C......66.39 O...... —
S........5.00

COAL CONSUMPTION, .793 LBS./KWH WITH INJECTION
20% OVERALL SO_2 REMOVAL FROM GAS (10%/UNIT STOICHIOMETRY)
PARTICULATE COLLECTION EFFICIENCY, 99.64%

ESTIMATED COMPOSITION OF GAS TO STACK EXCLUDING NO_x, % BY VOLUME

CO_2	SO_2	O_2	N_2	H_2O	TOTAL
12.43	.24	5.39	74.42	7.52	100.00

[a] BASIS
HEAT VALUE OF COAL, 12,000 BTU/LB (AS FIRED BASIS)
75% OF ASH IN COAL EVOLVES AS FLY ASH
LIMESTONE TO SYSTEM CONTAINS 95.0% $CaCO_3$ (DRY BASIS) AND 5% H_2O
LIMESTONE DRIED TO 0.5% H_2O PRIOR TO GRINDING
PARTICULATE RATES IN LBS./HR. SHOULD BE ADDED TO GAS RATES TO OBTAIN THE TOTAL STREAM RATE
HEAT FOR DRYING SUPPLIED BY COMBUSTION OF NO. 2 FUEL OIL WITH 20% EXCESS AIR
MATERIAL LOSSES ARE EXCLUDED FROM MATERIAL BALANCE

FIGURE 7 DRY LIMESTONE INJECTION PROCESS MATERIAL BALANCES[a]

Table 3

Actual Fixed Investment for 20 Ton/Hour Dry Limestone Injection Facilities on Shawnee Power Plant Unit No. 10 1969-70 Construction

Direct Cost	Equipment	Labor	Materials	Direct Subtotal
General Yard Work				
Landscaping	$	$	$ 1,600	$ 1,600
Guard Rails		82	218	300
Relocate access road		121	230	351
Yard lighting		9,128	2,515	11,643
Storage area		1,468	3,023	4,491
Raw water piping		362	25	387
Drains		401	166	567
Subtotal	$	$ 11,562	$ 7,777	$ 19,339
Limestone Storage and Feed Systems				
Truck hopper	$ 905	$		
Railroad car unloader	5,180	12,305	4,463	28,033
Truck hopper unloader	5,180			
Limestone receiving hopper	No cost			
Truck unloading conveyor	12,000			
Limestone storage conveyor	17,212	12,112	6,029	48,944
Limestone feed to dryer conveyor	1,591			
Subtotal	$ 42,068	$ 24,417	$ 10,492	$ 76,977
Limestone Drying System				
Limestone dryer, drive and combustion chamber with combustion equipment	$ 46,522			
Cyclone dust collector-6500 cfm	1,876	$ 6,989	$ 3,193	$ 59,365
Trickle valve	85			
Chutes & duct	700			
Dust collecting fan	4,300	677	258	5,435
Dust duct to precipitator		10,910	2,348	13,258
Bucket elevator and drive	4,010	1,550	450	6,010
Dryer shed		9,464	3,843	13,307
Subtotal	$ 57,693	$ 29,590	$ 10,092	$ 97,375
Limestone Grinding System				
Surge bin - 1000 cu.ft.	$ 1,748			
Structural supports	5,360	$ 8,807	$ 3,436	$ 22,360
Rotary valve with drive	1,304			
Volumetric feeder	1,705			
Ball mill, drive and oiling system	91,326			
Recirculation fan & drive - 23,000 cfm	3,836	16,656	4,730	119,958
Ducts and chutes	3,410			
Classifier and drive	4,600	2,872	1,196	14,028
Structural supports	5,360			
Storage silo - 6600 cu.ft.	7,360			
Structural supports	11,731			
Cyclone - 25,000 cfm	3,836			
Trickle valve	85	27,120	12,829	71,363
Bag filter - 595 sq.ft. filter area	5,968			
Exhaust fan with drive	1,130			
Rotary valve with drive	1,304			
Subtotal	$150,063	$ 55,455	$ 22,191	$ 227,709

Table 3 (continued)

	Equipment	Labor	Materials	Direct Subtotal
Limestone Injection System				
Rotary valve with drive	1,304	1,658	320	14,186
Transport pump with drive	4,936			
Transport air compressor	5,968			
Cyclone - 630 cfm	512	14,179	3,358	22,712
Feed tank - 300 cu.ft.	1,748			
Bag filter - 530 cfm	1,611			
Rotary valve with drive	1,304			
Screw conveyors with drive (2)	1,705	5,414	184	9,911
Air locks with drives (2)	2,608			
Air receiving tank	4,186	6,737	771	26,954
Injection air compressor with drive	7,502			
Transport air compressor with drive	7,502			
Limestone distributors	256			
Subtotal	$ 41,142	$ 27,988	$ 4,633	$ 73,763
Equipment Foundations	$	$ 37,951	$ 27,096	$ 65,047
Instrumentation	6,373	23,820	10,172	40,365
Control panel and shed		1,369	356	1,725
Subtotal	$ 6,373	$ 25,189	$ 10,528	$ 42,090
Piping				
Drying system		2,953	1,606	4,559
Grinding system	6,089	12,852	2,626	21,567
Injection system	24,877	52,245	5,336	82,458
Subtotal	$ 30,966	$ 68,050	$ 9,568	$ 108,584
Electrical Power Supply				
4160 volt board		1,714	9,042	10,756
480 volt board		70	77	147
Limestone injection board		190	325	515
Power and control wiring		27,206	11,775	38,981
Conduit		28,301	3,398	31,699
Cable trays		4,205	648	4,853
Grounding		2,172	245	2,417
Telephone		870	395	1,265
Subtotal		$ 64,728	$ 25,905	$ 90,633
Revision & Addition to Power House & Boiler				
Structural steel		$ 1,327	$ 1,540	$ 2,867
Floor grating		416	1,348	1,764
Miscellaneous metal work		6,679	864	7,543
Conduit, wiring and fixtures		1,236	644	1,880
Cooling water supply		30,765	5,709	36,474
Steam lines		5,967	223	6,190
Insulation	9,490	(Contract)		9,490
Ash disposal piping		6,216	13,408	19,624
Boiler additions (injection ports)		39,379	4,552	43,931
Subtotal	$ 9,490	$ 91,985	$ 28,288	$ 129,763
Painting		$ 28,008	$ 1,885	$ 29,893
Misc. Stairs, Grating and Handrails		$ 20,244	$ 7,225	$ 27,469
Test Probes - Installation	$	$ 46,262	$ 5,678	$ 51,940
Inspection and Testing		29,054	2,835	31,889
Direct Total - All Catagories	$337,795	$560,483	$174,193	$1,072,471

Table 3 (continued)

Indirect Cost	Equipment	Labor	Materials	Direct Subtotal
Construction General Expense				$ 106,365
Contractor's Engineering and Fee				169,687
TVA Engineering and Overhead				129,058
Indirect Total				405,110
TOTAL PROJECT FIXED INVESTMENT				$1,477,581

Table 4

Major Area Investment Requirements and Exponential Scale Factors for Dry Limestone Injection Facilities [a]

Major process equipment area	Base 1972 investment, $	Exponential scaling factor based on limestone throughput
General yard work	22,400	.50
Limestone storage and feed system	111,100	.80
Limestone drying system	137,600	.50
Limestone grinding system	309,500[b]	b
Limestone injection system	160,100	.40
Equipment foundations	75,500	.60
Instrumentation	51,400	.25
Piping	126,000	.50
Electrical power supply	105,100	.45
Revisions & additions to powerhouse and boiler	150,500	.50
Incremental electrostatic precipitator system	c	c
Incremental solids disposal system for collecting and sluicing limestone solids to pond	c	c

a. Capacity = 20 tons limestone/hr.
b. Based on updated vendor proposals
c. Not scaled according to limestone throughput

costs for a 150 MW plant were estimated by Cottrell Environmental Systems, Incorporated (3) for each combination of sulfur content and injection stoichiometry, based on the change in properties of the particulates and the additional amount to be removed as a result of dry limestone injection. Costs were then scaled according to power unit size using an exponent of 0.85.

The design for incremental solids disposal systems was based on minimum requirements as indicated by vendors. These investment costs were projected for each individual installation taking into consideration the quantity of injection solids to be disposed and the minimum recommended pipeline size.

The sum of the investment requirements for each major process area is called direct investment. The indirect costs for the project, including engineering design and project supervision, construction expense, contractor fees, and contingency are added to the direct investment to obtain the total fixed capital investment. Indirect investment is estimated as a percentage of direct investment (10) and is based on power unit size as follows:

	Indirect investment costs, percentage of direct investment existing power units			
	50 MW	150 MW	250 MW	350 MW
Engineering design and supervision	9	8	8	8
Construction expense	14	13	12	12
Contractors' fees	9	8	8	7
Contingency	13	13	13	13
Total indirects	45	42	41	39

Annual operating cost—On-stream time and power plant load are key factors in establishing annual operating costs for any process. For power systems, these factors may vary for different plants within the overall system due to electricity demand and maintenance. For purposes of projection, annual operating costs are estimated on the basis of 5,000 hrs operation/yr at full load.

The following is a listing of the breakdown established for projecting annual operating costs:

A. Direct costs
  1. Delivered raw material
    a. Limestone
  2. Conversion costs
    a. Operating labor and supervision including payroll overhead
    b. Utilities
      (1) Fuel oil (drying)
      (2) Sluice water
      (3) Electricity

- c. Maintenance
  - (1) Labor and material
- d. Analyses

B. Indirect costs
  1. Capital charges
  2. Overhead
     - a. Plant
     - b. Administrative

C. Annual operating cost (A and B)

D. Thermal effect of dry limestone injection on operating cost of power plant

E. Total annual cost (C and D)

Each of the above cost components accounts for a portion of the total annual operating cost, and is discussed below in order of relative importance.

1. Raw material - Limestone is the only raw material required for dry limestone injection. As indicated in a recent report prepared for EPA by the M. W. Kellogg Company (8), there are enormous deposits of carbonate rocks in the United States, and reserves are more than adequate for the foreseeable future. The major deposits, including two-thirds of all sulfur deposits, are located in the eastern half of the country where the vast majority of fossil fuel-fired power plants are located. Numerous reserves in these areas provide a nearby source of stone for most power plants.

Relative to the potential demand for limestone by power plants, production of these materials is quite large in most states; however, current production is inadequate to supply the potential needs of power plants in several Atlantic coastal regions, notably New England.

For a large majority of the power plants in the eastern half of the United States, high calcium limestone could be delivered for less than $6.00/ton. About half could obtain stone at less than $4.00/ton. Costs for power plants located in western states generally would be higher, because of the lack of suitable nearby deposits.

During the injection tests, the delivered cost of limestone at the Shawnee steam plant averaged $4.05/ton which is compatible with costs reported by Kellogg; therefore, a delivered cost of $4.05/ton of limestone is utilized for the case projections. For additional coverage, however, the sensitivity of other limestone prices on process operating costs will be shown in Section II.

2. Capital charges - The method for financing sulfur dioxide control processes is likely to depend upon the type of industry providing the investment capital and the nature of the control process, nonrecovery or product recovery type. In the past, it has been assumed that nonrecovery pollution control processes installed on power plants are financed on a regulated utility basis similar to the financing method for the initial power plant. This method of financing is also assumed for the nonrecovery dry limestone injection process in the projection of operating costs.

For the power industry (regulated utility economics), the usual practice of including in the capital charges a regulated return on investment and the state and Federal income taxes was followed (5). A breakdown of the capital charges is given in Table 5. The depreciation rate is straight line, based on the remaining life of the power plant after the pollution control process is installed, and is a percentage of initial fixed investment. Property insurance is also based on original fixed investment. However, because most regulatory commissions base the annual permissible return on investment on the remaining depreciation base (that portion of the original investment yet to be recovered or "written off"), the portion of annual capital charge to be applied to the operating cost declines uniformly over the life of the investment.

Table 5

Annual Capital Charges for Power Industry Financing
(Existing Power Unit with 15-Yr. Remaining Life)

	As percentage of original investment
Depreciation (based on 15-yr. remaining life for an existing power unit)	6.7
Insurance	0.5
Total rate applied to original investment	7.2
	As percentage of outstanding depreciation base[a]
Cost of capital (capital structure assumed to be 50% debt and 50% equity)	
Bonds at 8% interest	4.0
Equity at 12% return to stockholder	6.0
Taxes	
Federal (50% of gross return or same as return on equity)	6.0
State (national average for states in relation to Federal rates)	4.8
Total rate applied to depreciation base	20.8

a. Original investment yet to be recovered or "written off."

Annual return on equity, interest on outstanding debt, and income taxes are established in the same manner. The cost of money to the power industry is assumed to be 8% interest on borrowed funds and 12% return on equity money to attract investors. Assuming a capital structure of 50% debt and 50% equity, the overall cost of money under regulated economics comes to 10%. Federal income taxes are assumed to be 50% of gross income and state tax is assumed to be 80% of the national tax; the resulting state tax is higher than for nonregulated industry, but it is about the nationwide average for power companies.

The fairly well defined return on investment for the power company makes a low rate of depreciation acceptable, and return on investment can be logically included in production cost because it is a fixed charge usually passed on to the power customer.

For convenience in presenting annual operating cost results, average capital charges based on initial fixed investment are utilized since it is not practical to present the variable declining balance portion of the charge. For presentation in this manner, capital charges which normally account for depreciation and insurance are unchanged at 7.2% of original investment. Charges associated with the cost of capital and taxes are applied as an average charge equivalent to 10.4% of initial investment. (10.4% x original investment = 20.8% x average undepreciated investment). When assessed in this manner, the overall rate is equivalent to 17.6% of the original investment.

The average capital charge multiplied by the number of years of operation gives the same actual outlay of dollars as the declining balance calculation; however, the present worth of the two methods is different (discounted to 1972 dollars). There is, of course, another method (sinking fund depreciation plus interest, or capital recovery factor) of presenting a single annual percentage of initial investment which gives the same present worth of the lifetime capital charges as the declining balance calculation approach, but the actual dollar outlay is different. Of the two procedures, the average capital charge method has been chosen for annual operating cost tables because it can incorporate straight line depreciation, thus permitting simpler adjustment of the percentage of initial investment for power units with various remaining lives.

3. Utilities - During the dry limestone injection test program, utility usages were measured for the following three processing functions:

a. Limestone receiving, drying and conveying
b. Limestone grinding, classifying, and transport to feed tank
c. Limestone injection into boiler

In addition, utility requirements peripheral to the process such as additional water and electricity for solids disposal were estimated. The following utility usage rates are projected:

Process area	Utility projections Fuel oil	 Sluice water	 Electricity
a. Limestone receiving, drying and conveying	5.3 gal/ ton limestone	-	6.0 kWh/ton limestone
b. Limestone grinding, classifying, and transport to feed tank	-	-	53.4 kWh/ton limestone
c. Limestone injection into boiler	-	-	9.6 kWh/ton limestone
Peripheral area			
d. Particulate collection	-	-	Credit[a]
e. Additional solids disposal	-	b	1.925 kWh/thousand gal of sluice water

Electricity usage rates for particulate collection varies for each case as indicated by Cottrell Environmental Systems, Inc. However, CES indicates that the total amount of electricity required for dust collection is less due to dry limestone injection than is normally required for collecting fly ash alone; therefore, an operating cost credit is claimed equivalent to the electricity saved. Unit costs which areincorporated in the case projections for utilities are shown below:

Utility	Unit cost
No. 2 fuel oil (drying)	$0.11/gal.
Sluice water	.03/M gal.
Electricity	.007/kWh

Fuel oil cost is based on an acutal 1972 published price for Chicago, Illinois (7). Costs for sluice water and electricity are also 1972 prices; however, they are somewhat higher than typical power plant costs to compensate for the additional generation demand placed on the power unit and to account for the more rapid capital recovery for the additional facilities than required for new plants.

4. Operating labor and supervision - Operating labor requirements for the dry limestone injection tests at Shawnee were somewhat high due to the extensive amount of monitoring required for the numerous sampling probes which were utilized. Consequently,

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a. Electricity requirements are reduced as a result of different resistivities of the solids. Amount of reduction depends upon sulfur content and injection stoichiometry.

b. Sluice water is dependent upon disposal system design rather than total solids disposal.

projections of operating labor are somewhat lower than incurred during the tests. Since labor requirements are primarily a function of limestone throughput and on-stream time, annual labor requirements at 8,760 hours/year (365 days) were estimated for four levels of injection at full load. These base labor requirements were then adjusted according to on-stream ratio using a 0.5 scaling exponent. The estimated labor breakdown at 8,760 hours/year and the adjusted total labor requirement for operation at 5,000 hours/year are shown in table 6.

Table 6

Estimated Labor Requirements for Dry Limestone Injection Process

	Estimated annual operating labor requirement, man-hrs. at 8,760 hours operation/year					
Limestone throughput, tons(dry)/hour	Heavy equipment operator (unloading)	Conveying, feeding and disposal	Plant operation	Supervision	Total	Adjusted total operating labor required man hours at 5,000 hours operation/year
0-25	2,080	2,080	8,760	400	13,320	10,070
25-50	2,080	4,160	8,760	500	15,500	11,720
50-75	2,080	6,240	8,760	600	17,680	13,370
75-100	2,080	8,760	8,760	700	20,300	15,350

Based on 1972 TVA labor rates (13), a composite operating rate of $6.00/hr including overhead and supervisory expense is utilized for the evaluation. For the 52-case study, labor costs are not escalated over the life of the project. However, the effect of escalation at rates up to 10%/year is presented in Section II.

5. Maintenance - Solids drying and grinding usually are maintenance prone operations. Although actual operating data over an extended period of time is the best source of information for defining maintenance requirements, insufficient data was generated during the Shawnee program to accurately define these costs. Maintenance costs chargeable to the process are, therefore, estimates based on actual recorded data. For purposes of this study, precipitator maintenance is estimated as two percent of the precipitator fixed capital investment for 5,000 hours annual operation. A slightly higher maintenance charge ranging from 3.1 - 3.5% is projected for the combined drying grinding, injection, and solids disposal facilities. Specific areas which were maintenance prone, such as the hydroveyors in the sluice system, were recognized in arriving at these figures.

Maintenance costs usually increase over the life of a project; however, in the case of a power plant related system where on-stream time declines over the remaining life, estimating maintenance as a percentage of investment for a given on-stream time will probably suffice. Estimates for other on-stream times are scaled exponentially according to on-stream ratio using a 0.6 scaling exponent. Using this method, the maintenance per unit time increases over the project life as on-stream time decreases.

6. Overhead - Overheads are usually a complex function of plant and company size, and product research and marketing staff, and are likely to vary slightly from installation to installation. However, for consistency in the cost projections, a common method for

estimating overheads was established. In all of the cost projections plant overhead is estimated as 20% of conversion costs, and administrative overhead is estimated as 10% of operating labor. Although costs may vary widely for an actual installation, these projections are representative of the expected values.

7. Thermal effect of dry limestone injection - When limestone is injected into a boiler, the required coal-firing rate for the power unit is adversely affected by the level of injection stoichiometry for each sulfur content and must be adjusted to maintain the same power generating capacity prior to dry limestone injection. Based on operating data for Shawnee unit 10, a coal-firing rate of 0.780 lbs/kWh prior to injection is assumed for each power plant size considered. This firing rate is adjusted upward to compensate for the thermal effect of dry limestone injection as discussed in Appendix H, Additional Heat Requirement Calculations. Costs for the additional coal are estimated and displayed on the annual operating cost projections as the thermal effect of dry limestone injection on operating cost of power plant. This charge is equivalent to a coal cost of $6.00/ton and a processing cost of $0.30/ton, including incremental costs for grinding and conveying.

8. Analyses - Purchased limestone and waste solids are the only materials which require analyses in the dry limestone injection process. Since both of these materials are proportional, projections of analyses requirements are estimated on the basis of limestone throughput. Based on Shawnee experience, approximately 1 hour/day or 208 hours/year at an annual on-stream time of 5,000 hours is required for analyses at a limestone throughput of 20 tons/hour. Requirements for other limestone rates are proportional to the relative limestone usage. A rate of $10.00/hour including overhead, supplies, and supervisory expense is projected for laboratory work.

9. Working capital - For projection purposes, working capital for the dry limestone injection process may be estimated as the equivalent cost of a four weeks supply of raw material (limestone). Although the magnitude of the estimated working capital required for 5,000 hours annual operation varies from $2,600 for a 50 MW, 0.8% S coal, 3.0 injection stoichiometry installation to $153,000 for a 350 MW, 5.0% S coal, 4.0 injection stoichiometry installation, the effect on annual and lifetime operating costs at a cost of money of 10% is relatively small.

Lifetime Operating Costs—Under regulated economics, annual operating costs vary each year as the rate base declines due to depreciation "write-off" (the cost of money and income taxes are applied to undepreciated portion of investment); in addition, any changes in on-stream time of the power unit must be recognized. For any given case it is desirable, therefore, to have a year-to-year tabulation of operating costs. Furthermore, recognizing the time value of money, these annual operating costs should be discounted at the cost of money (10% for this study) to the initial year of operation for ready comparison of present worth to other pollution control means such as the annual costs required for low sulfur fuels.

The total life of a coal-fired power unit is about 30 years (5). For the 52 case parametric study, lifetime operating costs are based on 15 years remaining life of the power plant after installation of the dry limestone injection process; however, the effect of various other remaining lives is also studied. Historically, the operating usage of most power plants declines toward the end of their life. To reflect this experience, the following declining load operating profile is assumed during the remaining years of operation:

Plant age, years	Plant remaining life, years	Annual operation, (on-stream time) hours at full generating capacity
16 - 20	15 - 11	5,000
21 - 25	10 - 6	3,500
26 - 30	5 - 1	1,500

Lifetime operating cost analyses are extremely valuable in evaluation of regulated investments. They are an accumulation of each year's cost and, therefore, are more representative of actual outlays for process operation.

Since rate of investment profitability is prescribed under regulated economics, the data generated by the tabulation of lifetime operating costs indicates the total effect of pollution abatement on the cost of power to the consumer. Actual and present worth lifetime costs are, therefore, projected for each of the cases as overall measures of process economics. In addition, equivalent lifetime unit operating costs expressed as $/ton coal burned, mills/kWh, and $/ton sulfur removed are presented.

II. Summary of Results and Conclusions

Results of the 52 Case Parametric Study

Investment—The estimated total fixed investment requirements for the dry limestone injection process are summarized in table 7 for each of the 52 cases established. Abbreviated investment estimates which show the major area investment costs are given in tables A-1 to A-52 of Appendix A in Process Economics Section. It should be mentioned that the system used in these projections is one of minimum cost, and may not be compatible to all potential users of the process. The estimated investment requirements would be higher for power plants which require additional pond facilities for disposal of solids, or for systems with other combinations of existing dust collection facilities. The effect of these additional requirements is discussed later.

Table 7

Total Fixed Investment Requirements for Dry Limestone Injection Process
Applied to Existing Power Units Equipped with
Mechanical and Electrostatic Dust Collectors in Series[a]

Sulfur in coal	Injection stoichiometry,	Total fixed investment							
		50 MW units		150 MW units		250 MW units		350 MW units	
%	moles CaO injected per mole sulfur in coal	$	$/kW	$	$/kW	$	$/kW	$	$/kW
0.8	3.0	751,500	15.0	1,280,100	8.5	1,695,100	6.8	2,032,300	5.8
0.8	4.0	834,500	16.7	1,431,500	9.5	1,868,100	7.5	2,278,800	6.5
0.8	5.0	908,300	18.2	1,568,800	10.5	2,086,100	8.3	2,503,200	7.2
0.8	6.0	975,000	19.5	1,694,400	11.3	2,253,600	9.0	2,707,700	7.7
0.8	7.0	1,036,300	20.7	1,808,000	12.1	2,407,700	9.6	2,893,300	8.3
3.0	1.0	817,100	16.3	1,404,600	9.4	1,865,600	7.5	2,238,600	6.4
3.0	2.0	1,070,500	21.4	1,874,200	12.5	2,498,900	10.0	3,005,900	8.6
3.0	3.0	1,271,500	25.4	2,251,400	15.0	3,011,400	12.0	3,676,800	10.5
3.0	4.0	1,442,000	28.8	2,574,200	17.2	3,498,000	14.0	4,262,100	12.2
5.0	1.0	995,300	19.9	1,736,200	11.6	2,314,500	9.3	2,782,700	8.0
5.0	2.0	1,332,900	26.7	2,369,500	15.8	3,221,100	12.9	3,927,000	11.2
5.0	3.0	1,602,600	32.1	2,926,600	19.5	3,968,400	15.9	4,766,400	13.6
5.0	4.0	1,838,700	36.8	3,376,200	22.5	4,582,000	18.3	5,645,500	16.1

a. Fixed investment includes cost of additional electrostatic precipitator for reducing dust emission to same level obtained prior to installation of dry limestone injection process. Additional pond disposal area not included.

The total fixed investment for the dry limestone injection process ranges from \$751,500 (\$15.0/kW) for a 50 MW - 0.8% S coal-fired unit with an injection stoichiometry of 3.0 to \$5,645,500 (\$16.1/kW) for a 350 MW - 5.0% S coal-fired unit with an injection stoichiometry of 4.0; however, unit investment costs vary from \$5.8 to \$36.8/kW depending upon power unit size, sulfur in coal, and injection stoichiometry.

The effect of power unit size and injection stoichiometry on total dry limestone process investment is shown in figures 8, 9, and 10 for the three variations in sulfur content of coal. The relationship between sulfur content of coal and injection stoichiometry on total fixed investment for a 150 MW power unit is presented in figure 11.

Relative investment cost distribution—The relative distribution of direct investment costs for the three base cases is shown in table 8. As indicated, the limestone grinding system and the incremental electrostatic precipitator system are the major investment items for the process. Although the distribution of estimated costs varies somewhat for each of

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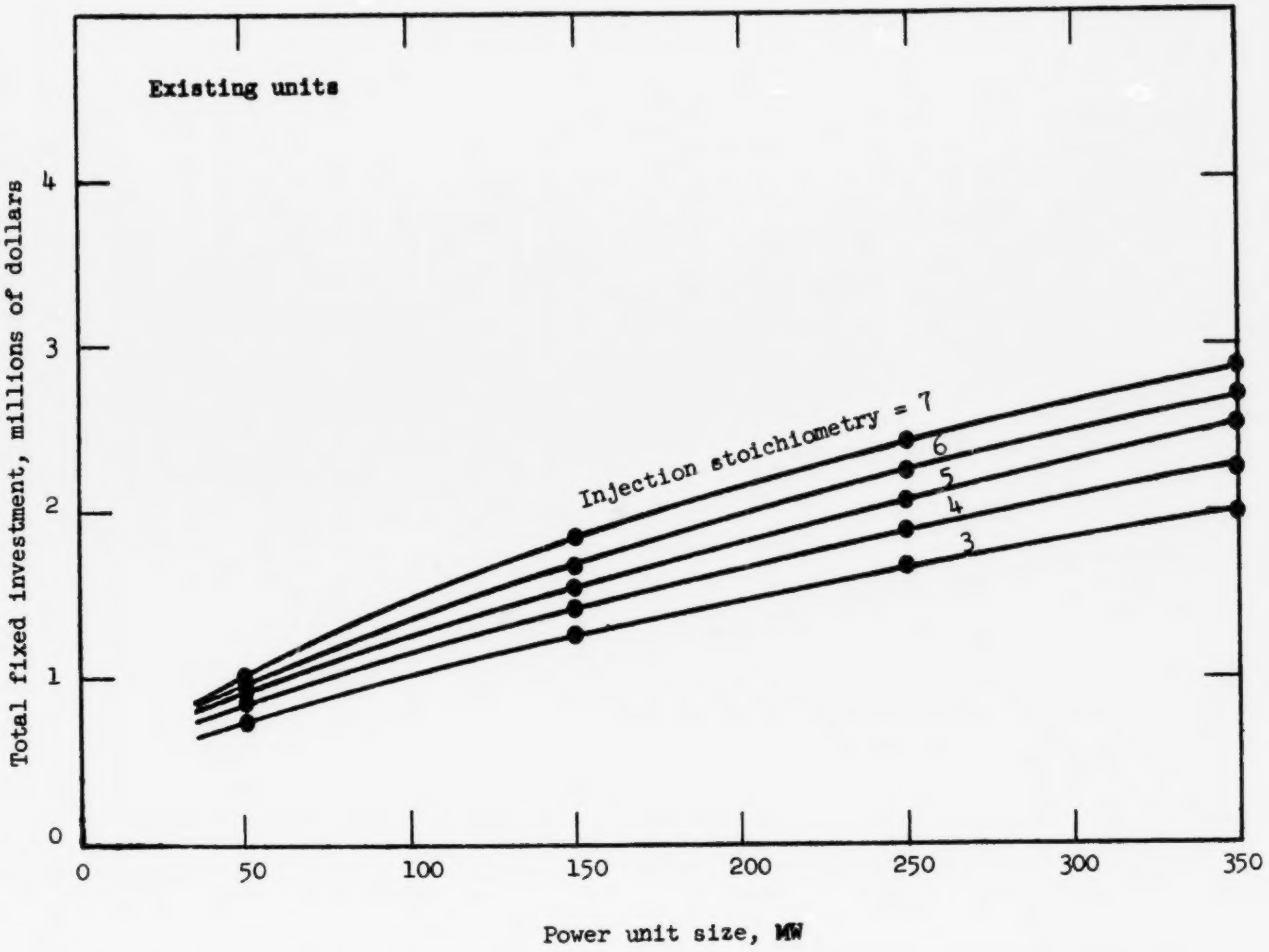

Figure 8 . Effect of Power Unit Size and Injection Stoichiometry on Total Dry Limestone Process Investment: 0.8% S Coal

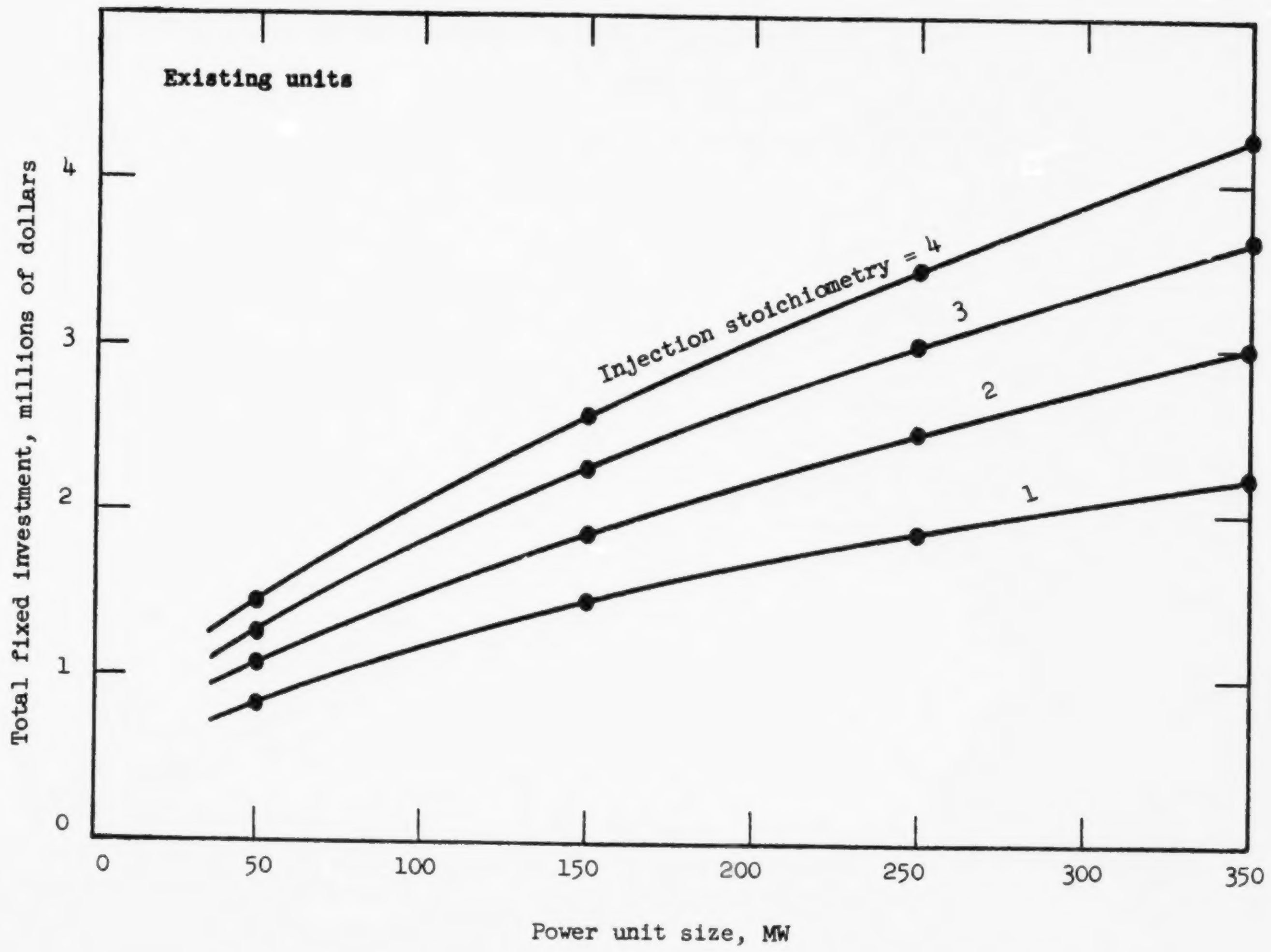

Figure 9. Effect of Power Unit Size and Injection Stoichiometry on Total Dry Limestone Process Investment: 3.0% S Coal

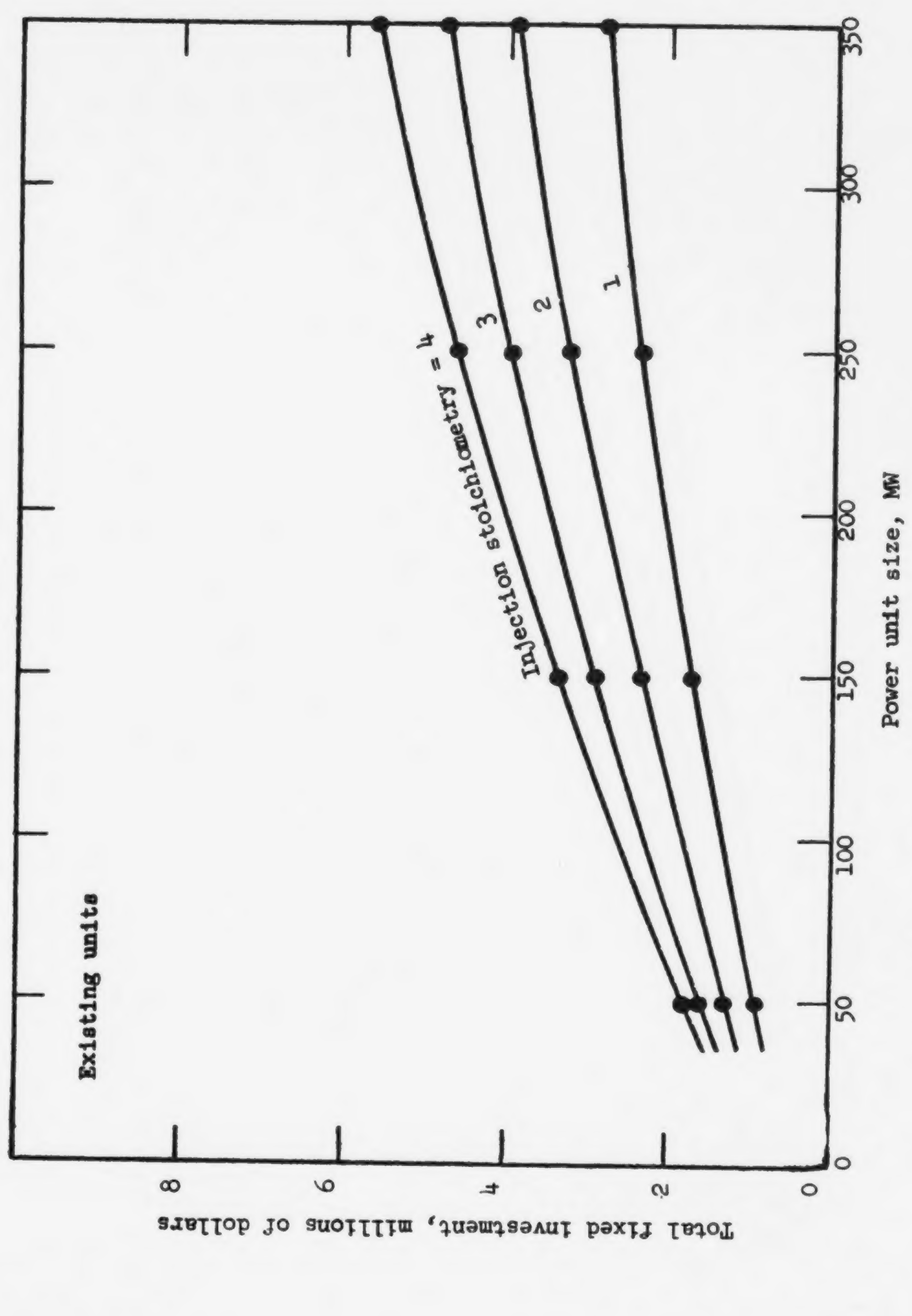

Figure 10. Effect of Power Unit Size and Injection Stoichiometry on Total Dry Limestone Process Investment: 5.0% S Coal

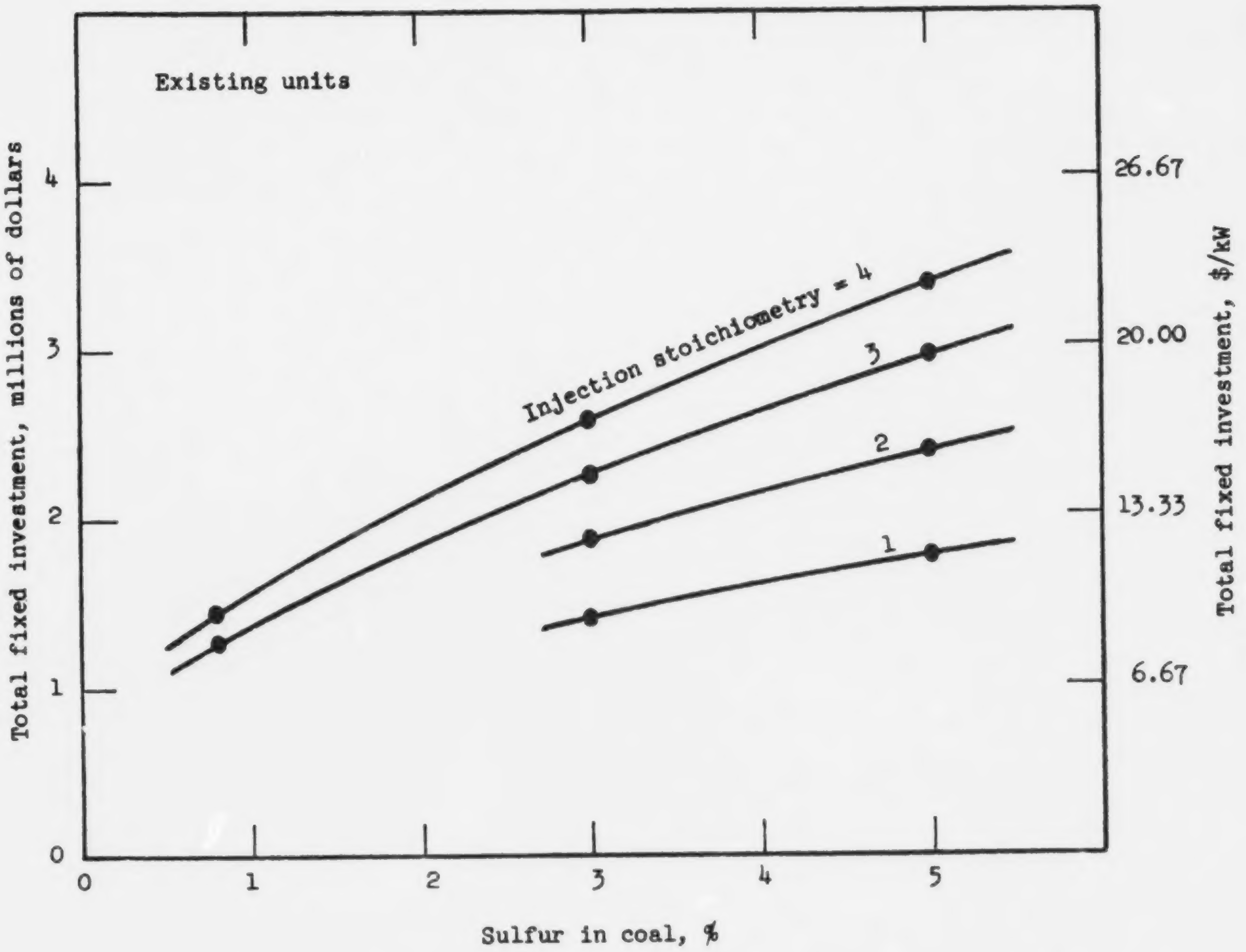

Figure 11. Effect of Sulfur Content of Coal and Injection Stoichiometry on Total Dry Limestone Process Investment: 150 MW Units

Table 8

Relative Distribution of Projected Direct Investment Costs for Dry Limestone Injection Process

Process area	Relative investment distribution, % of subtotal direct investment 150 MW - 0.8% S 5.0 stoich.	150 MW - 3.0% S 2.0 stoich.	150 MW - 5.0% S 2.0 stoich.
General yard work	1.3	1.3	1.3
Limestone storage and feed system	4.7	5.5	6.5
Limestone drying system	7.7	8.0	8.2
Limestone grinding system	15.1	16.5	18.3
Limestone injection system	9.9	9.8	9.5
Equipment foundations	3.9	4.1	4.5
Instrumentation	3.7	3.4	3.1
Piping	7.1	7.3	7.5
Electrical power supply	6.2	6.2	6.2
Revisions and additions to powerhouse and boiler	8.5	8.7	8.9
Incremental electrostatic precipitator system	22.8	21.6	20.0
Incremental solids disposal system	9.1	7.6	6.0
Total direct investment	100.0	100.0	100.0

the 52 cases, these distributions indicate the relative contribution of each processing area to the subtotal direct costs.

Annual operating cost—Based on an annual operation of 5,000 hours/year, projected operating cost results of the 52-case parametric study are summarized in tables 9, 10, and 11 for each of the three levels of sulfur in coal. Detailed breakdowns of these projected annual costs are presented in tables A-53 through A-104 of Appendix A.

Average annual operating costs range from $298,400 ($3.05/ton coal burned) for a 50 MW - 0.8% S coal-fired unit with an injection stoichiometry of 3.0 to $4,122,700 ($5.85/ton coal burned) for a 350 MW 5.0% S coal-fired unit with an injection stoichiometry of 4.0. Unit operating costs vary from $1.23 to $8.72/ton coal burned, or from 0.48 to 3.51 mills/kWh. Operating costs per ton of sulfur removed decrease with increasing power unit size and injection stoichiometry. These unit costs range from $316/ton sulfur removed for a 350 MW - 5.0% S coal-fired unit with an injection stoichiometry of 4.0 to $2,664/ton sulfur removed for a 50 MW - 0.8% S coal-fired unit with an injection stoichiometry of 3.0.

Based on the results given in the tables, the effects of several variables on operating costs are presented graphically.

Table 9

Average Annual Operating Cost for Dry Limestone Injection Process Under Regulated Economics 0.8% Sulfur Coal[a]

Power unit size, MW	Injection stoichiometry, moles CaO injected per mole sulfur in coal	Average annual cost, $	Unit operating cost $/ton coal	mills /kWh	$/ton S removal
50	3.0	298,400	3.05	1.19	2664
50	4.0	331,300	3.38	1.33	2301
50	5.0	362,800	3.69	1.45	1972
50	6.0	392,300	3.99	1.57	1816
50	7.0	420,800	4.27	1.68	1644
150	3.0	501,600	1.71	0.67	1529
150	4.0	580,900	1.97	0.78	1345
150	5.0	656,600	2.23	0.88	1207
150	6.0	730,100	2.47	0.97	1127
150	7.0	801,500	2.71	1.07	1054
250	3.0	681,300	1.39	0.55	1217
250	4.0	796,000	1.62	0.64	1106
250	5.0	920,300	1.87	0.74	998
250	6.0	1,034,100	2.10	0.83	958
250	7.0	1,145,200	2.32	0.92	895
350	3.0	843,800	1.23	0.48	1076
350	4.0	1,006,000	1.47	0.58	998
350	5.0	1,162,400	1.69	0.66	902
350	6.0	1,315,100	1.91	0.75	870
350	7.0	1,477,100	2.14	0.84	824

a. Existing units - 15 yrs. remaining life
5000 hrs. operation/yr

Table 10

Average Annual Operating Cost for Dry Limestone Injection Process Under Regulated Economics 3.0% Sulfur Coal[a]

Power unit size, MW	Injection stoichiometry, moles CaO injected per mole sulfur in coal	Average annual cost, $	Unit operating cost		
			$/ton coal	mills /kWh	$/ton S removal
50	1.0	323,100	3.30	1.29	1188
50	2.0	435,100	4.42	1.74	800
50	3.0	536,400	5.42	2.15	651
50	4.0	631,700	6.36	2.53	576
150	1.0	561,800	1.91	0.75	695
150	2.0	835,200	2.83	1.11	512
150	3.0	1,091,400	3.68	1.46	443
150	4.0	1,337,300	4.48	1.78	406
250	1.0	773,100	1.58	0.62	568
250	2.0	1,197,800	2.43	0.96	440
250	3.0	1,612,100	3.26	1.29	391
250	4.0	2,018,100	4.06	1.61	368
350	1.0	965,900	1.41	0.55	507
350	2.0	1,547,400	2.25	0.88	406
350	3.0	2,120,500	3.06	1.21	368
350	4.0	2,667,100	3.83	1.52	348

a. Existing units - 15 yrs. remaining life
5000 hrs. operation/yr

Table 11

Average Annual Operating Cost for Dry Limestone Injection Process Under Regulated Economics 5.0% Sulfur Coal[a]

Power unit size, MW	Injection stoichiometry, moles CaO injected per mole sulfur in coal	Average annual cost, $	Unit operating cost		
			$/ton coal	mills /kWh	$/ton S removal
50	1.0	399,300	4.06	1.60	876
50	2.0	569,300	5.74	2.28	624
50	3.0	726,400	7.27	2.91	525
50	4.0	878,000	8.72	3.51	471
150	1.0	748,000	2.54	1.00	550
150	2.0	1,174,500	3.95	1.57	429
150	3.0	1,611,000	5.38	2.15	389
150	4.0	2,012,800	6.66	2.68	360
250	1.0	1,061,200	2.16	0.85	465
250	2.0	1,762,000	3.56	1.41	386
250	3.0	2,426,800	4.86	1.94	351
250	4.0	3,081,500	6.12	2.47	331
350	1.0	1,351,200	1.96	0.77	412
350	2.0	2,307,000	3.33	1.32	361
350	3.0	3,198,800	4.57	1.83	330
350	4.0	4,122,700	5.85	2.36	316

a. Existing units - 15 yrs. remaining life
5000 hrs. operation/yr

The effects of sulfur content of coal and injection stoichiometry on annual and unit operating costs for a 150 MW installation are shown in figure 12. Figures 13, 14, and 15 indicate the relationship between power unit size, injection stoichiometry, and annual operating costs for each of the three levels of sulfur. The effects of injection stoichiometry and power unit size on unit operating cost expressed as both $/ton coal burned and mills/kWh are indicated in figures 16 and 17 for 0.8 and 3.0% S coals. Although somewhat higher costs are obtained, the relationship for 5.0% sulfur coal is similar. Unit operating costs per ton of sulfur removed are shown in figures 18, 19, and 20 for each of the three levels of sulfur in coal.

Relative operating cost distribution—The relative distribution of projected annual operating costs for the three base cases at an annual on-stream time of 5,000 hours is shown in table 12. As shown in the table, limestone cost and capital charges are the two most prominent cost items. Although the relative cost distribution of each item changes somewhat with variations in power unit size, sulfur content of fuel, and injection stoichiometry, the other cost components are of minor importance in relation to the annual costs for limestone and capital charges.

Lifetime operating cost—Based on the operating profile established for the 52 case parametric study, lifetime operating costs were projected. Results of these projections are summarized in tables 13, 14, and 15 for the three levels of sulfur in coal. Computer print-outs which show the year-to-year operating costs corresponding to these lifetime projections are presented in tables A-105 to A-156 of Appendix A. In addition to the actual outlay annual values shown in these printouts, both actual and discounted overall total costs and unit costs either per ton of coal burned or mills per kilowatt hour are presented.

Lifetime operating costs range from $3,909,400 (present worth = $2,223,900) for a 50 MW - 0.8% S coal-fired unit with an injection stoichiometry of 3.0 to $47,281,000 (present worth = $27,443,100) for a 350 MW - 5.0% S coal-fired unit with an injection stoichiometry of 4.0. Lifetime unit operating costs are somewhat higher than average annual operating costs due to the pronounced effect of the declining operating profile assumed for the power plant.

The effect of power unit size and injection stoichiometry on (1) lifetime total operating cost, (2) lifetime unit operating cost, $/ton coal burned and (3) lifetime unit operating cost, $/ton sulfur removed, is shown in figures 21, 22, and 23, respectively, for a 0.8% S coal-fired installation. Both present worth and actual costs are indicated over the complete range of injection stoichiometries utilized for the parametric study. Figures 24, 25, and 26 show similar relationships for a 3.0% S coal-fired installation with an injection stoichiometry of 2.0. Relationships for a 5.0% S coal-fired installation with an injection stoichiometry of 2.0 are shown in figures 27, 28, and 29.

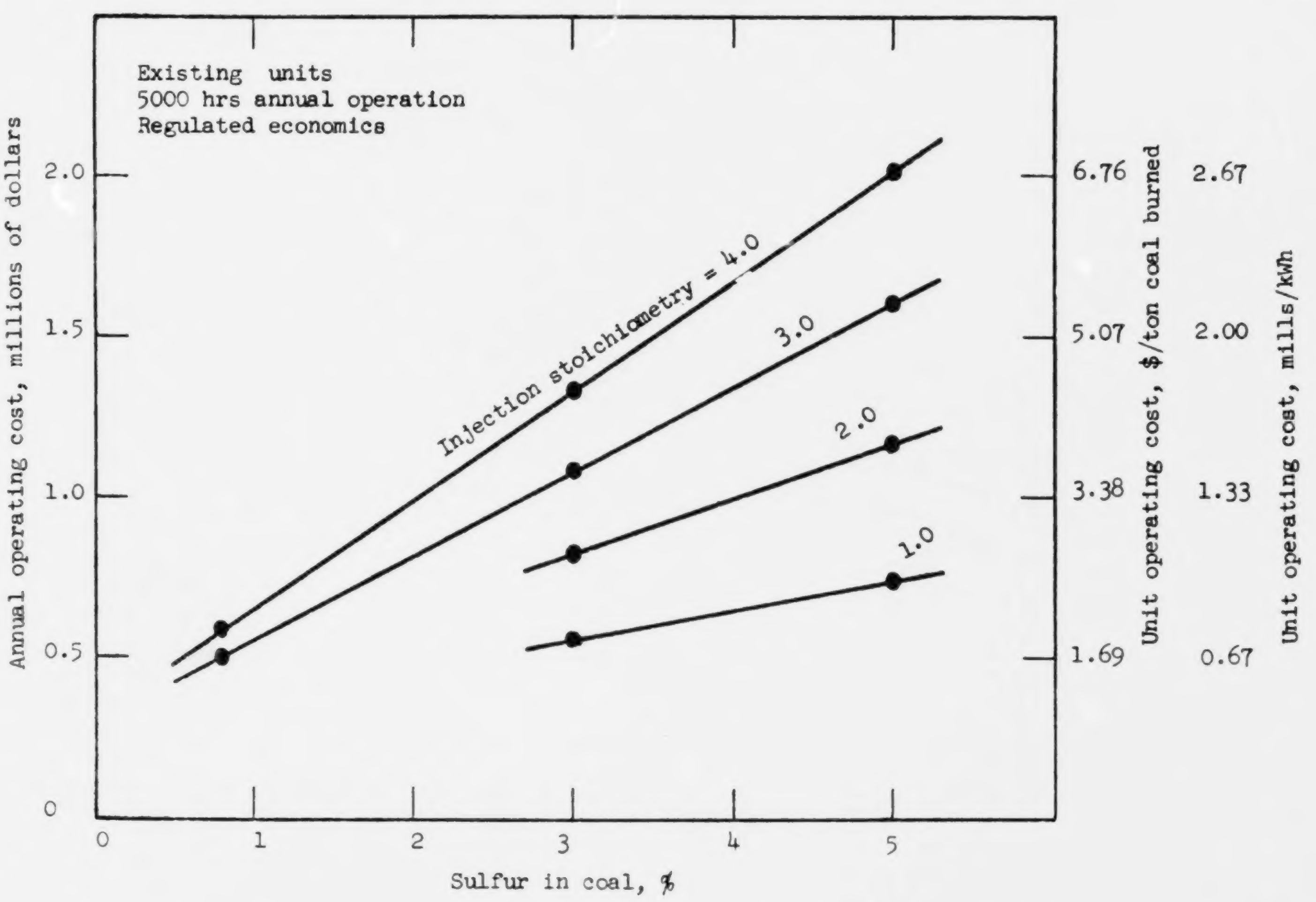

Figure 12. Effect of Sulfur Content of Coal and Injection Stoichiometry on Annual and Unit Operating Cost of Dry Limestone Process: 150 MW Units

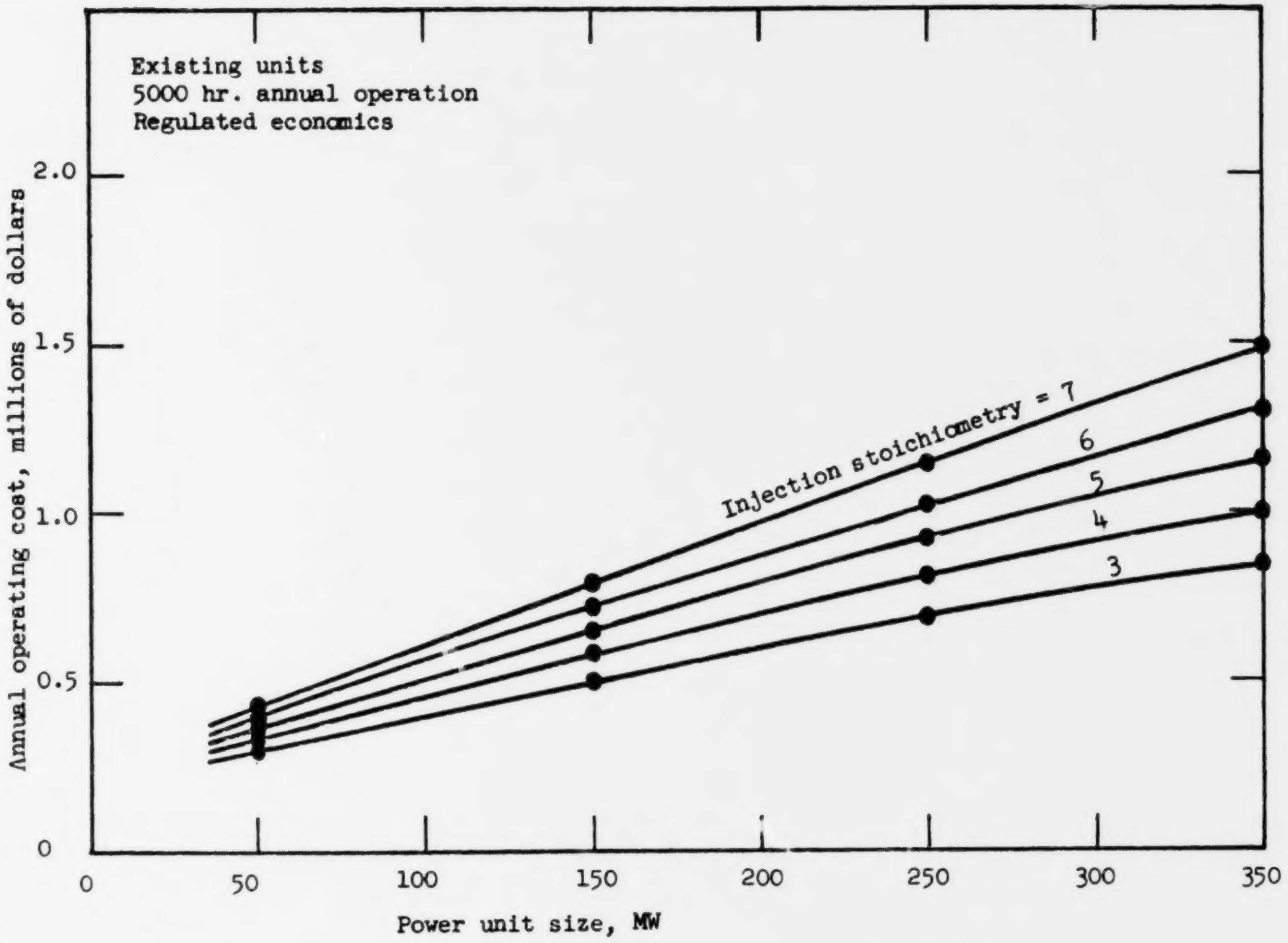

Figure 13. Effect of Power Unit Size and Injection Stoichiometry on Annual Operating Cost of Dry Limestone Process: 0.8% S Coal

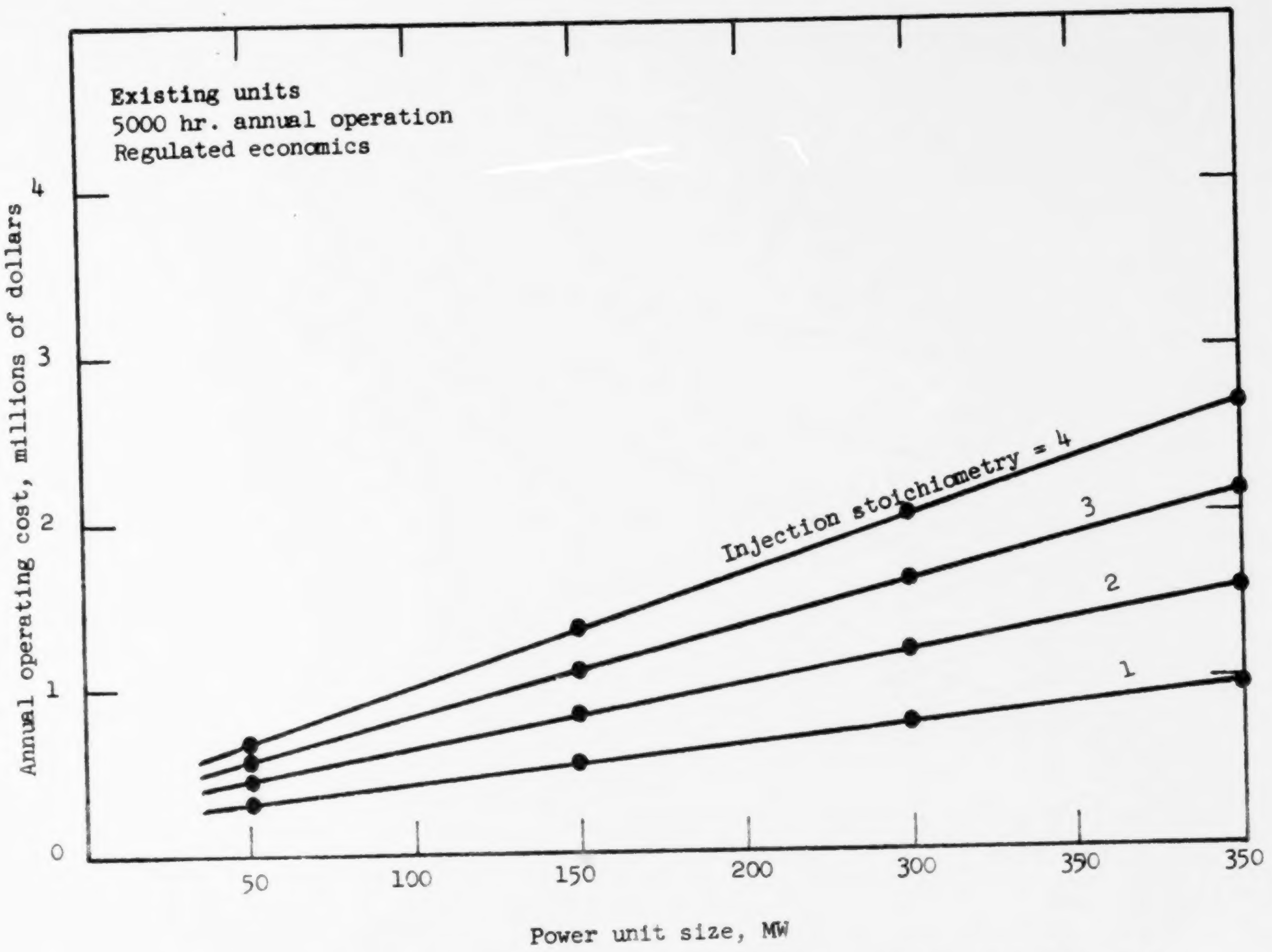

Figure 14. Effect of Power Unit Size and Injection Stoichiometry on Annual Operating Cost of Dry Limestone Process: 3.0% S Coal

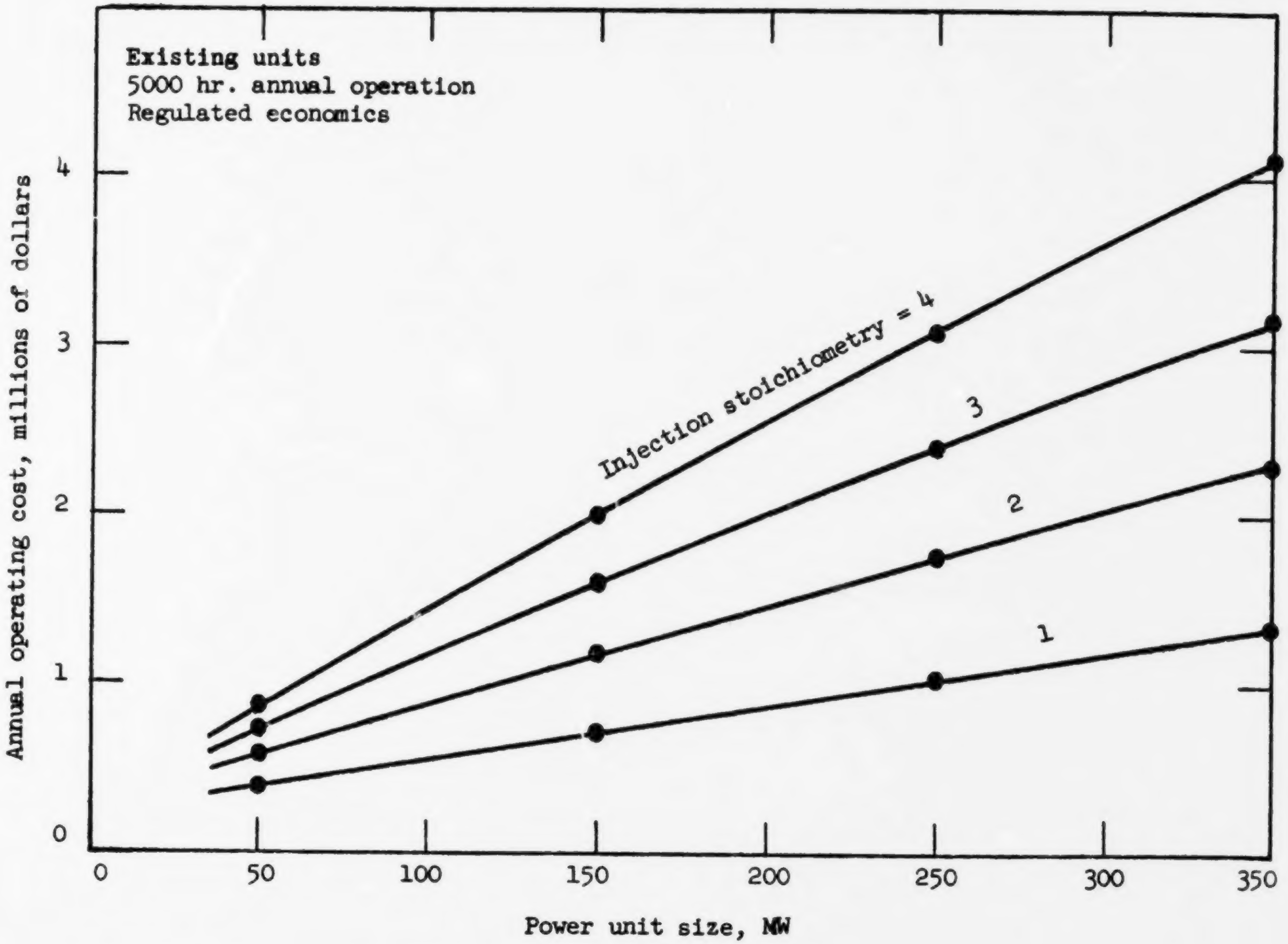

Figure 15 . Effect of Power Unit Size and Injection Stoichiometry on Annual Operating Cost of Dry Limestone Process: 5.0% S Coal

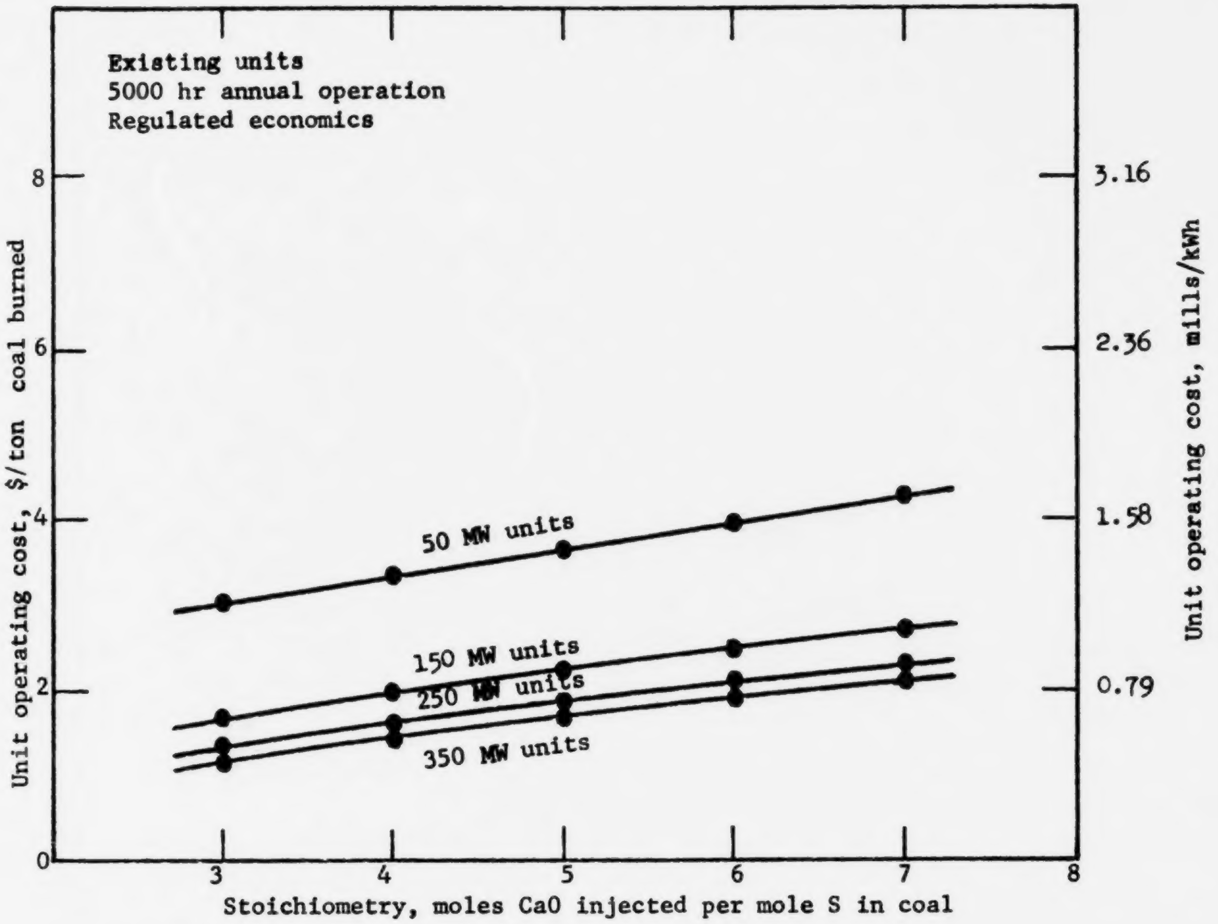

Figure 16. Effect of Injection Stoichiometry and Power Unit Size on Unit Operating Cost of Dry Limestone Process: 0.8% S Coal

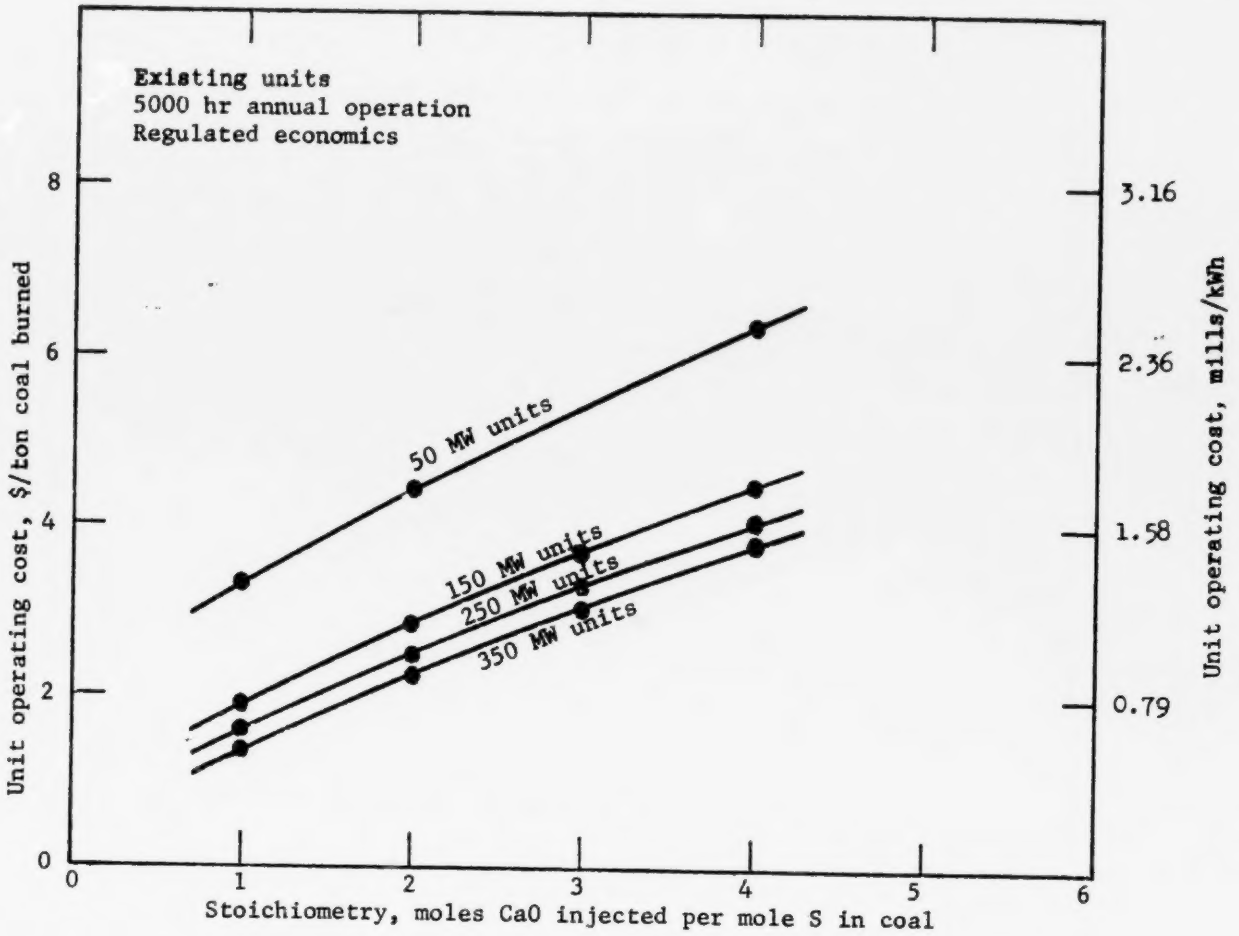

Figure 17. Effect of Injection Stoichiometry and Power Unit Size on Unit Operating Cost of Dry Limestone Process: 3.0% S Coal

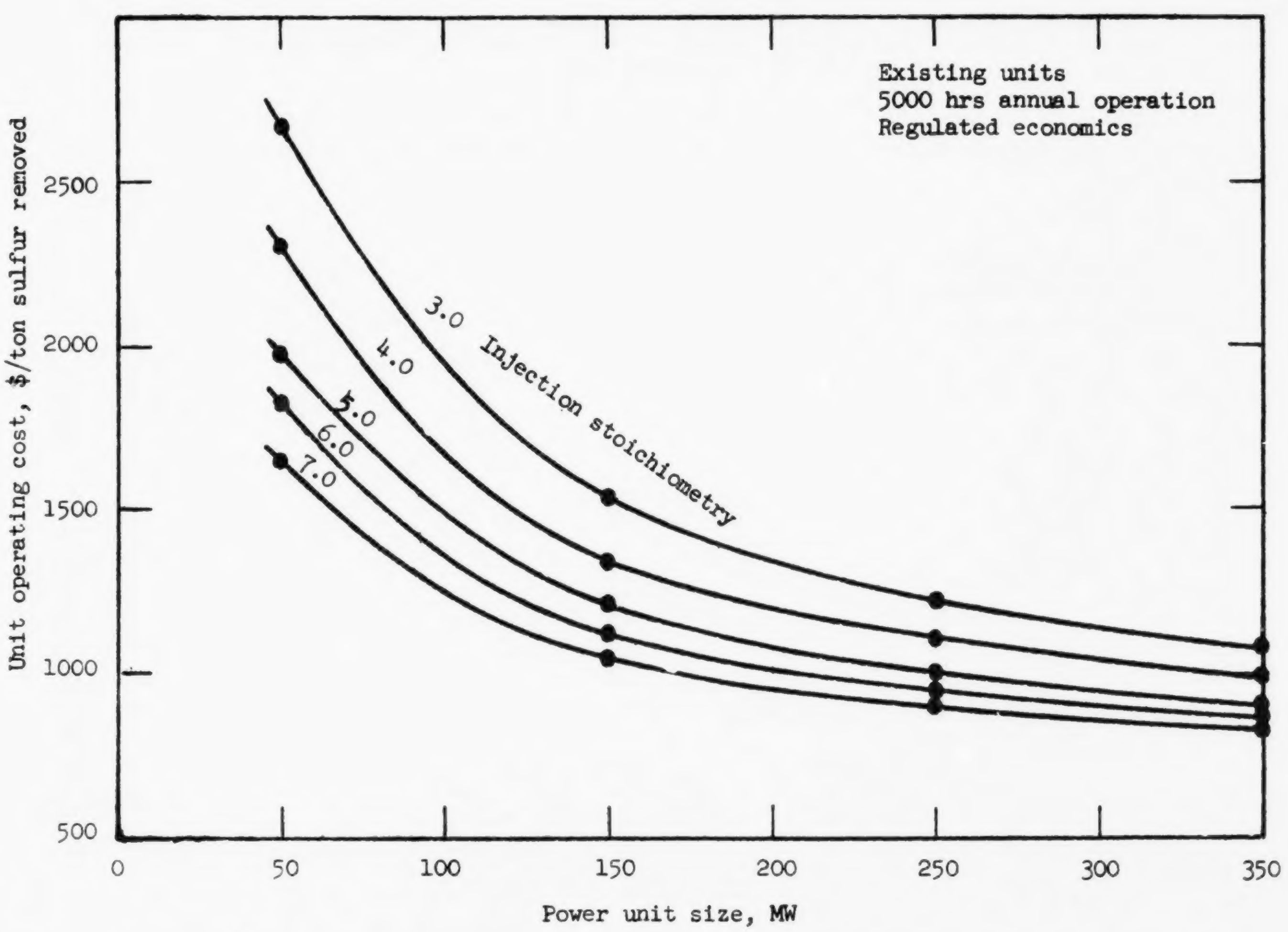

Figure 18. Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Sulfur Removed: 0.8% S Coal

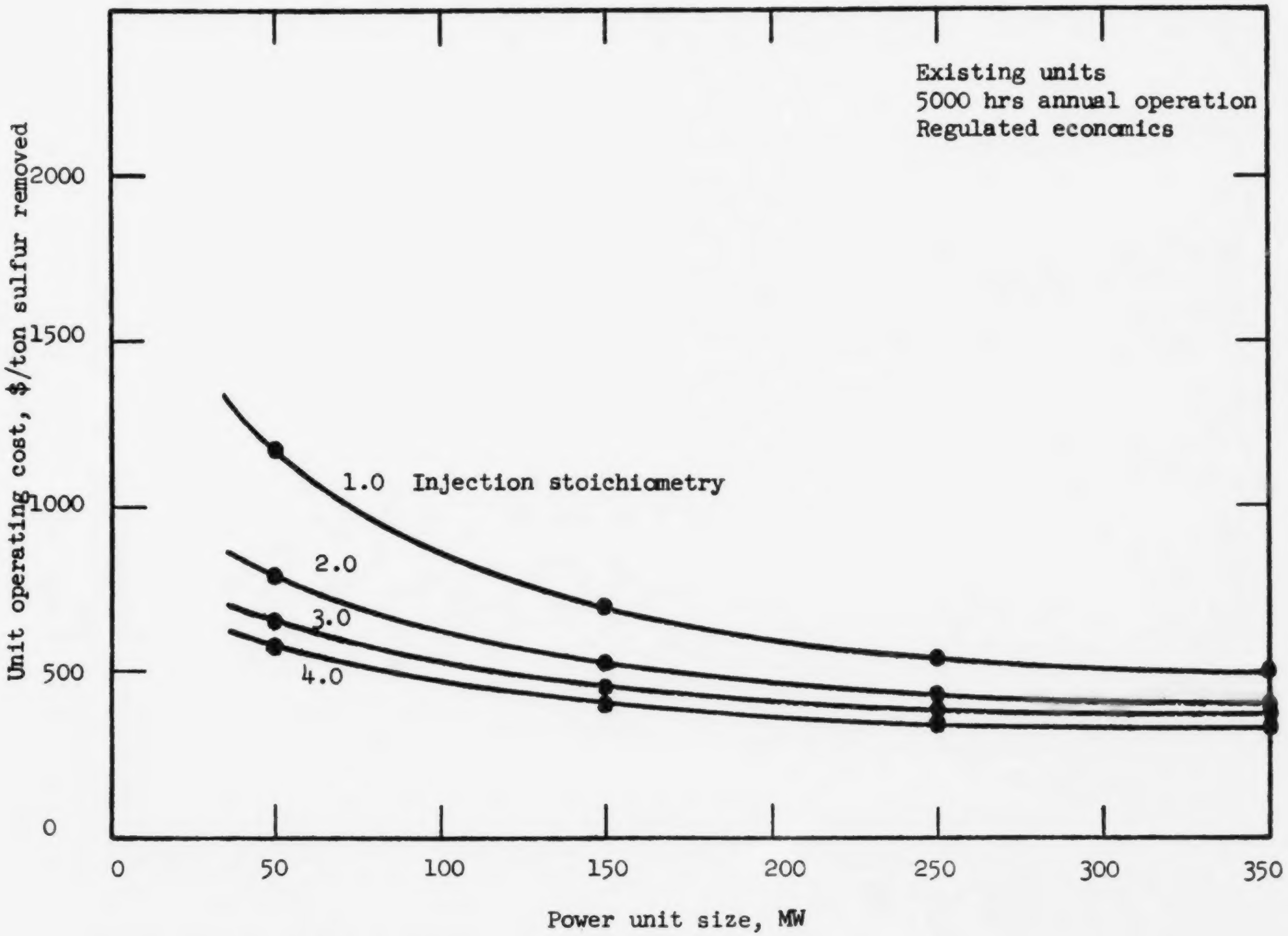

Figure 19. Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Sulfur Removed: 3.0% S Coal

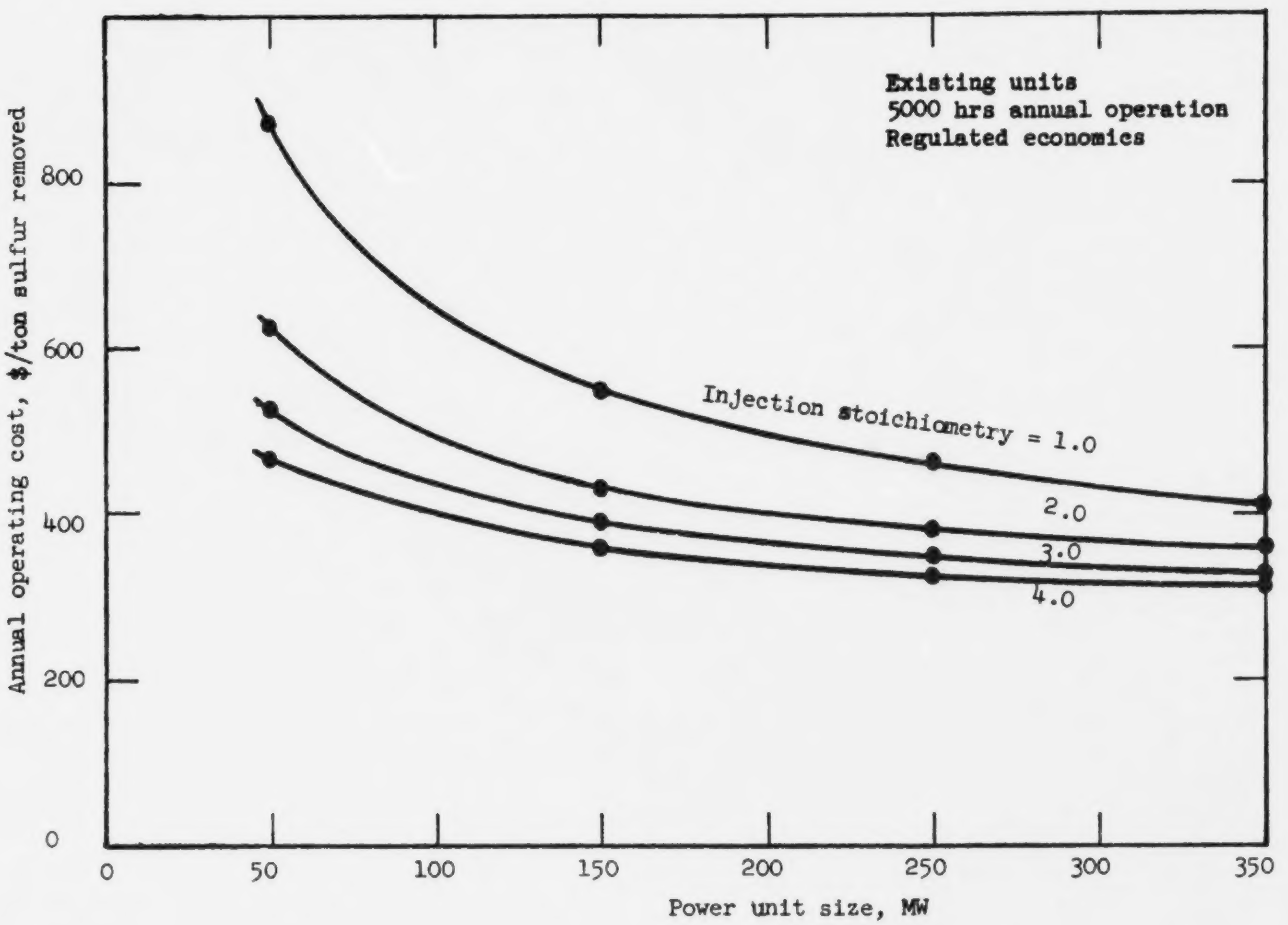

Figure 20. Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Sulfur Removed: 5.0% S Coal

Table 12

Relative Distribution of Projected Operating Costs for Dry Limestone Injection Process

	150 MW - 0.8% S 5.0 stoich.	150 MW - 3.0% S 2.0 stoich.	150 MW - 5.0% 2.0 stoich.
DIRECT COSTS			
Delivered raw material			
Limestone	25.2	29.8	35.6
Conversion costs			
Operating labor and supervision	9.2	7.2	5.2
Utilities			
Fuel oil	3.6	4.3	5.1
Sluice water	1.2	1.0	0.7
Electricity	3.4	3.8	4.5
Maintenance			
Drying, grinding, injection & solids disposal area	6.1	5.8	5.2
Dust collection	1.1	1.0	0.8
Analyses	0.2	0.2	0.1
INDIRECT COSTS			
Average capital charges	42.1	39.5	35.5
Overhead			
Plant	4.9	4.6	4.3
Administrative	0.9	0.7	0.5
Thermal effect of dry limestone injection on operating cost of power plant	2.1	2.1	2.5
Total operating cost	100.0	100.0	100.0

Table 13

Lifetime Operating Cost for Dry Limestone Injection Process Under Regulated Economics 0.8% Sulfur Coal[a]

Power unit size, MW	Injection stoichiometry, moles CaO injected per mole sulfur in coal	Lifetime operating cost (net increase in cost of Power)				Cumulative present worth of net increase in cost of power, discounted at 10%/yr			
		$	$/ton coal	mills/kWh	$/ton S removed	$	$/ton coal	mills/kWh	$/ton S removed
50	3.0	3,909,400	3.99	1.56	3491	2,223,900	2.27	0.89	1986
50	4.0	4,326,400	4.41	1.73	3004	2,464,300	2.51	0.99	1711
50	5.0	4,715,000	4.80	1.89	2563	2,689,400	2.74	1.08	1462
50	6.0	5,081,600	5.16	2.03	2353	2,901,100	2.95	1.16	1343
50	7.0	5,428,600	5.51	2.17	2121	3,102,100	3.15	1.24	1212
150	3.0	6,489,000	2.21	0.87	1978	3,712,400	1.26	0.49	1132
150	4.0	7,438,200	2.53	0.99	1722	4,262,400	1.45	0.57	987
150	5.0	8,337,700	2.83	1.11	1533	4,784,000	1.62	0.64	879
150	6.0	9,200,500	3.12	1.23	1420	5,284,900	1.79	0.70	816
150	7.0	10,030,300	3.39	1.34	1320	5,766,600	1.95	0.77	759
250	3.0	8,715,800	1.78	0.70	1556	4,999,800	1.02	0.40	893
250	4.0	10,038,500	2.05	0.80	1394	5,768,300	1.18	0.46	801
250	5.0	11,505,000	2.34	0.92	1251	6,619,100	1.35	0.53	719
250	6.0	12,818,800	2.61	1.03	1187	7,382,400	1.50	0.59	684
250	7.0	14,087,600	2.86	1.13	1101	8,120,000	1.65	0.65	634
350	3.0	10,696,900	1.56	0.61	1364	6,146,600	0.90	0.35	784
350	4.0	12,562,700	1.83	0.72	1246	7,230,600	1.05	0.41	717
350	5.0	14,358,000	2.09	0.82	1115	8,274,100	1.20	0.47	642
350	6.0	16,096,400	2.34	0.92	1065	9,285,400	1.35	0.53	614
350	7.0	17,930,200	2.60	1.02	1001	10,347,900	1.50	0.59	577

a. Existing units - 15 yrs. remaining life. Assumed operating profile:
5 yr @ 5000 hr/yr
5 yr @ 3500 hr/yr
5 yr @ 1500 hr/yr

Table 14

Lifetime Operating Cost for Dry Limestone Injection Process Under Regulated Economics 3.0% Sulfur Coal[a]

Power unit size, MW	Injection stoichiometry, moles CaO injected per mole sulfur in coal	Lifetime operating cost (net increase in cost of Power)				Cumulative present worth of net increase in cost of power, discounted at 10%/yr			
		$	$/ton coal	mills/kWh	$/ton S removed	$	$/ton coal	mills/kWh	$/ton S removed
50	1.0	4,227,100	4.31	1.69	1554	2,406,900	2.46	0.96	885
50	2.0	5,607,200	5.70	2.24	1031	3,205,200	3.26	1.28	589
50	3.0	6,826,500	6.90	2.73	828	3,911,300	3.95	1.56	475
50	4.0	7,955,200	8.00	3.18	726	4,565,900	4.59	1.83	417
150	1.0	7,220,700	2.46	0.96	894	4,135,700	1.41	0.55	512
150	2.0	10,438,200	3.53	1.39	640	6,002,800	2.03	0.80	368
150	3.0	13,388,600	4.51	1.79	543	7,717,400	2.60	1.03	313
150	4.0	16,181,700	5.43	2.16	491	9,342,200	3.13	1.25	283
250	1.0	9,808,700	2.00	0.78	721	5,633,500	1.15	0.45	414
250	2.0	14,708,000	2.99	1.18	541	8,480,000	1.72	0.68	312
250	3.0	19,404,000	3.92	1.55	471	11,207,900	2.27	0.90	272
250	4.0	23,965,700	4.82	1.92	437	13,863,600	2.79	1.11	253
350	1.0	12,121,000	1.77	0.69	637	6,973,000	1.02	0.40	366
350	2.0	18,751,600	2.72	1.07	492	10,824,500	1.57	0.62	284
350	3.0	25,199,100	3.64	1.44	437	14,573,700	2.10	0.83	253
350	4.0	31,268,000	4.49	1.79	408	18,110,200	2.60	1.03	236

[a] Existing units - 15 yrs. remaining life. Assumed operating profile: 5 yr @ 5000 hr/yr
5 yr @ 3500 hr/yr
5 yr @ 1500 hr/yr

Table 15

Lifetime Operating Cost for Dry Limestone Injection Process Under Regulated Economics 5.0% Sulfur Coal[a]

Power unit size, MW	Injection stoichiometry, moles CaO injected per mole sulfur in coal	Lifetime operating cost (net increase in cost of Power)				Cumulative present worth of net increase in cost of power, discounted at 10%/yr			
		$	$/ton coal	mills/kWh	$/ton S removed	$	$/ton coal	mills/kWh	$/ton S removed
50	1.0	5,172,200	5.26	2.07	1134	2,953,500	3.00	1.18	648
50	2.0	7,219,100	7.28	2.89	792	4,139,200	4.18	1.66	454
50	3.0	9,067,100	9.08	3.63	655	5,211,300	5.22	2.08	377
50	4.0	10,830,500	10.76	4.33	581	6,235,100	6.19	2.49	335
150	1.0	9,423,500	3.20	1.26	693	5,413,800	1.84	0.72	398
150	2.0	14,341,700	4.82	1.91	524	8,271,800	2.78	1.10	302
150	3.0	19,304,000	6.44	2.57	466	11,153,800	3.72	1.49	269
150	4.0	23,788,000	7.87	3.17	425	13,765,400	4.56	1.84	246
250	1.0	13,152,300	2.68	1.05	577	7,575,100	1.54	0.61	332
250	2.0	21,118,800	4.26	1.69	463	12,204,500	2.46	0.98	268
250	3.0	28,537,000	5.71	2.28	412	16,526,400	3.31	1.32	239
250	4.0	35,742,200	7.10	2.86	384	20,723,500	4.12	1.66	222
350	1.0	16,533,600	2.40	0.94	518	9,538,500	1.39	0.55	305
350	2.0	27,296,600	3.94	1.56	428	15,799,300	2.28	0.90	247
350	3.0	37,086,500	5.30	2.12	383	21,504,200	3.08	1.23	222
350	4.0	47,281,000	6.71	2.70	362	27,443,100	3.89	1.57	210

[a] Existing units - 15 yrs. remaining life. Assumed operating profile:
5 yr @ 5000 hr/yr
5 yr @ 3500 hr/yr
5 yr @ 1500 hr/yr

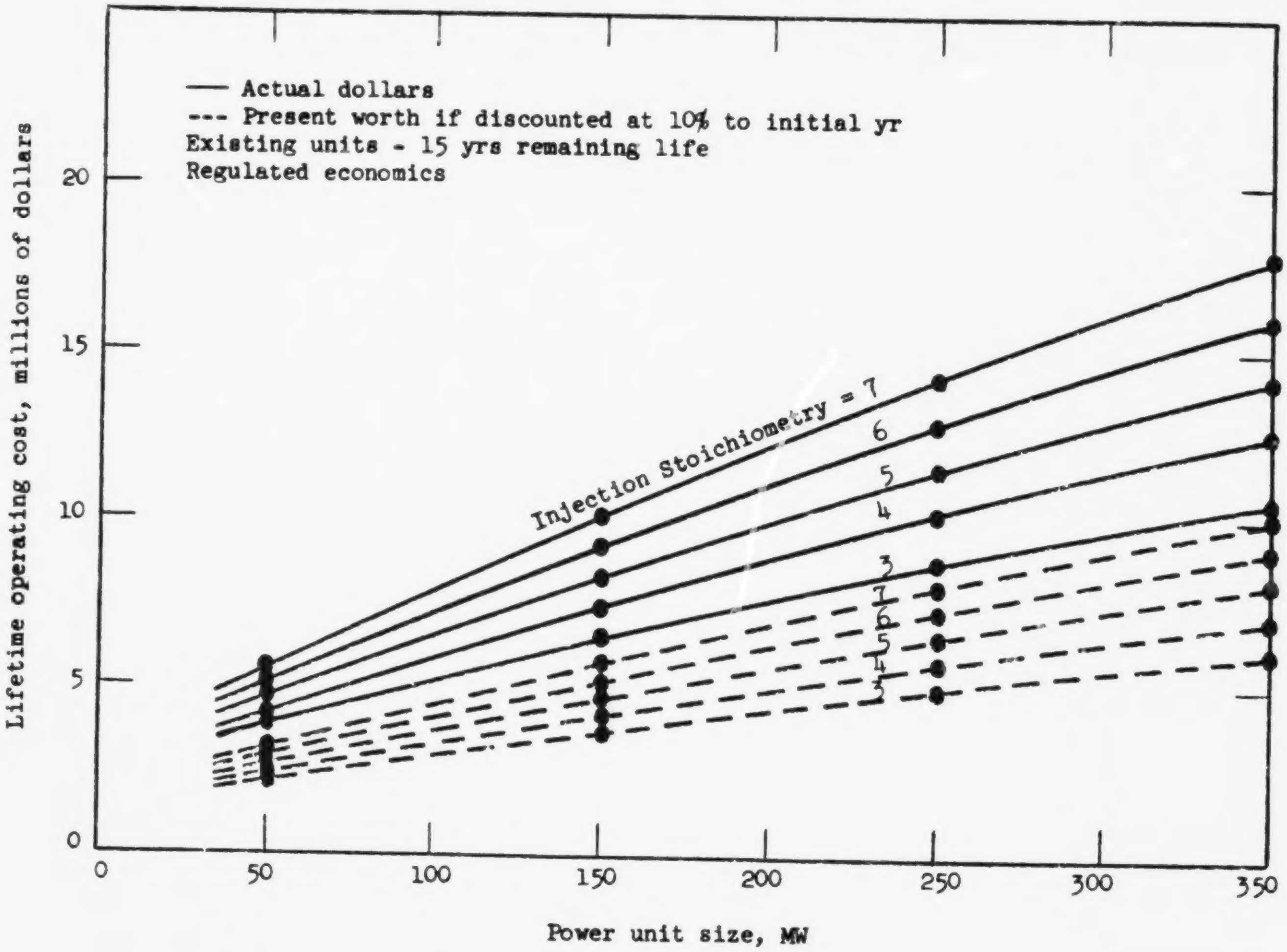

Figure 21. Effect of Power Unit Size and Injection Stoichiometry on Lifetime Increase in Cost of Power Using Dry Limestone Injection: 0.8% S Coal

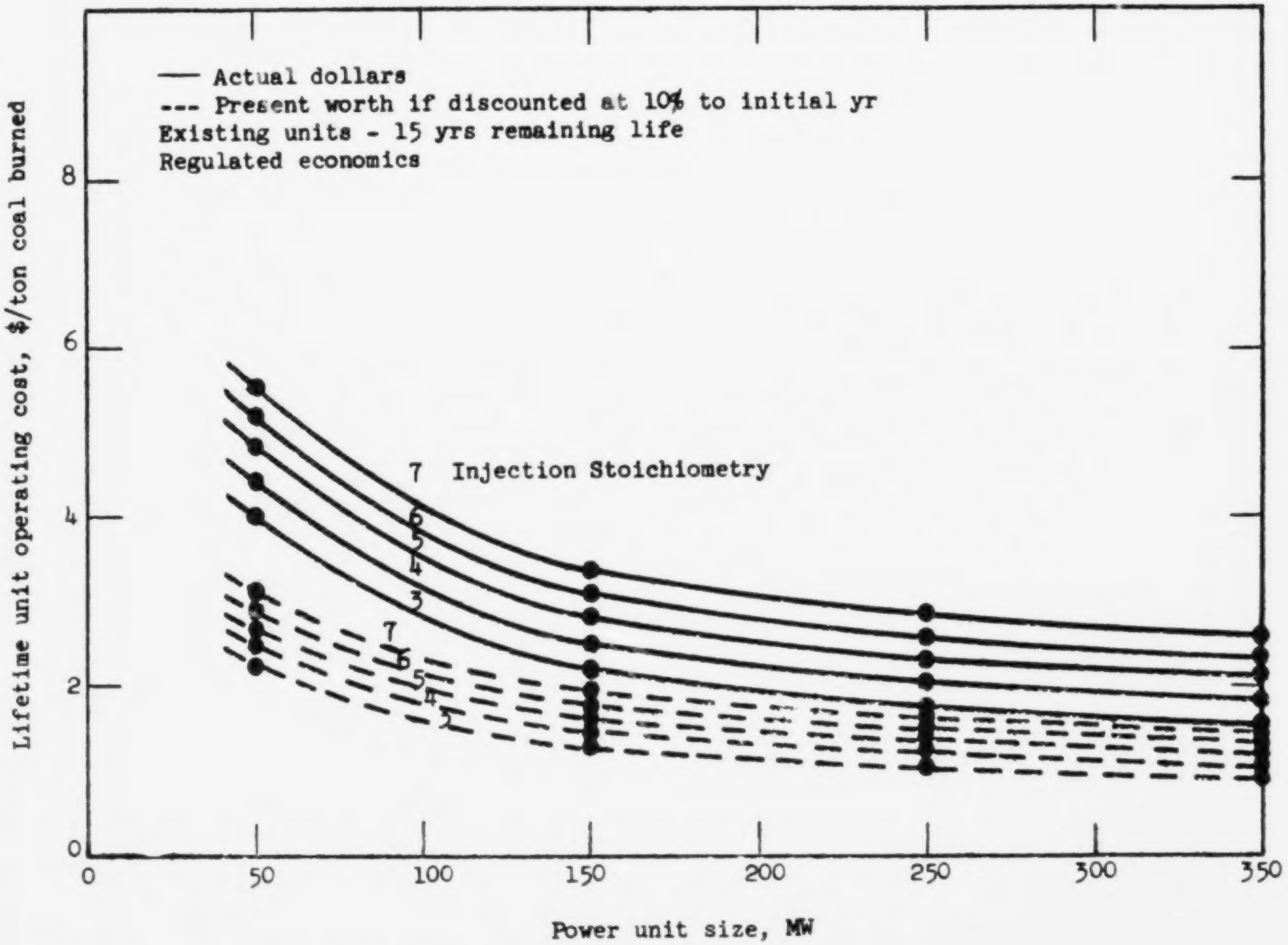

Figure 22. Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Coal Burned Over Life of Plant: 0.8% S Coal

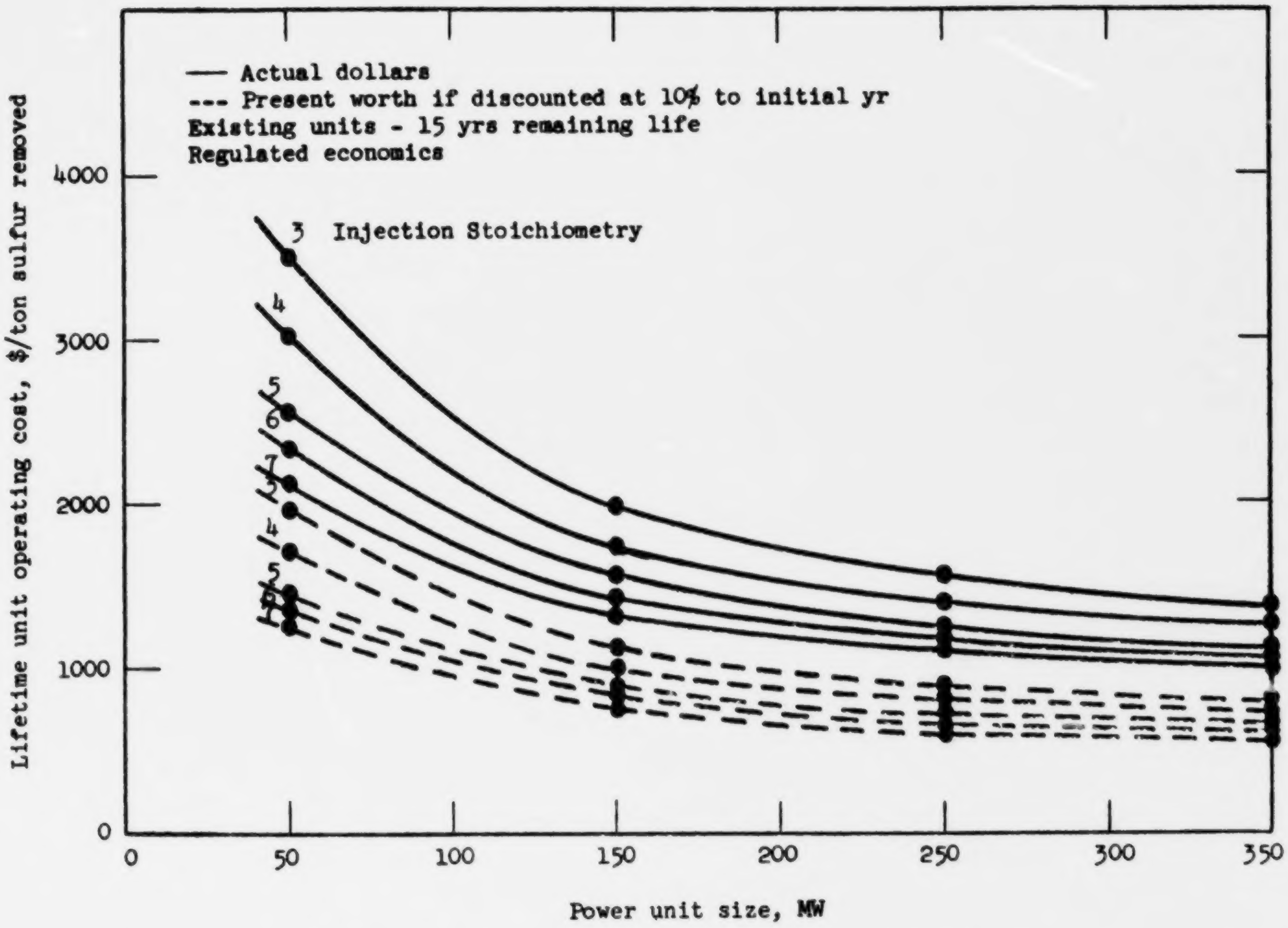

Figure 23. Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Sulfur Removed Over Life of Plant: 0.8% S Coal

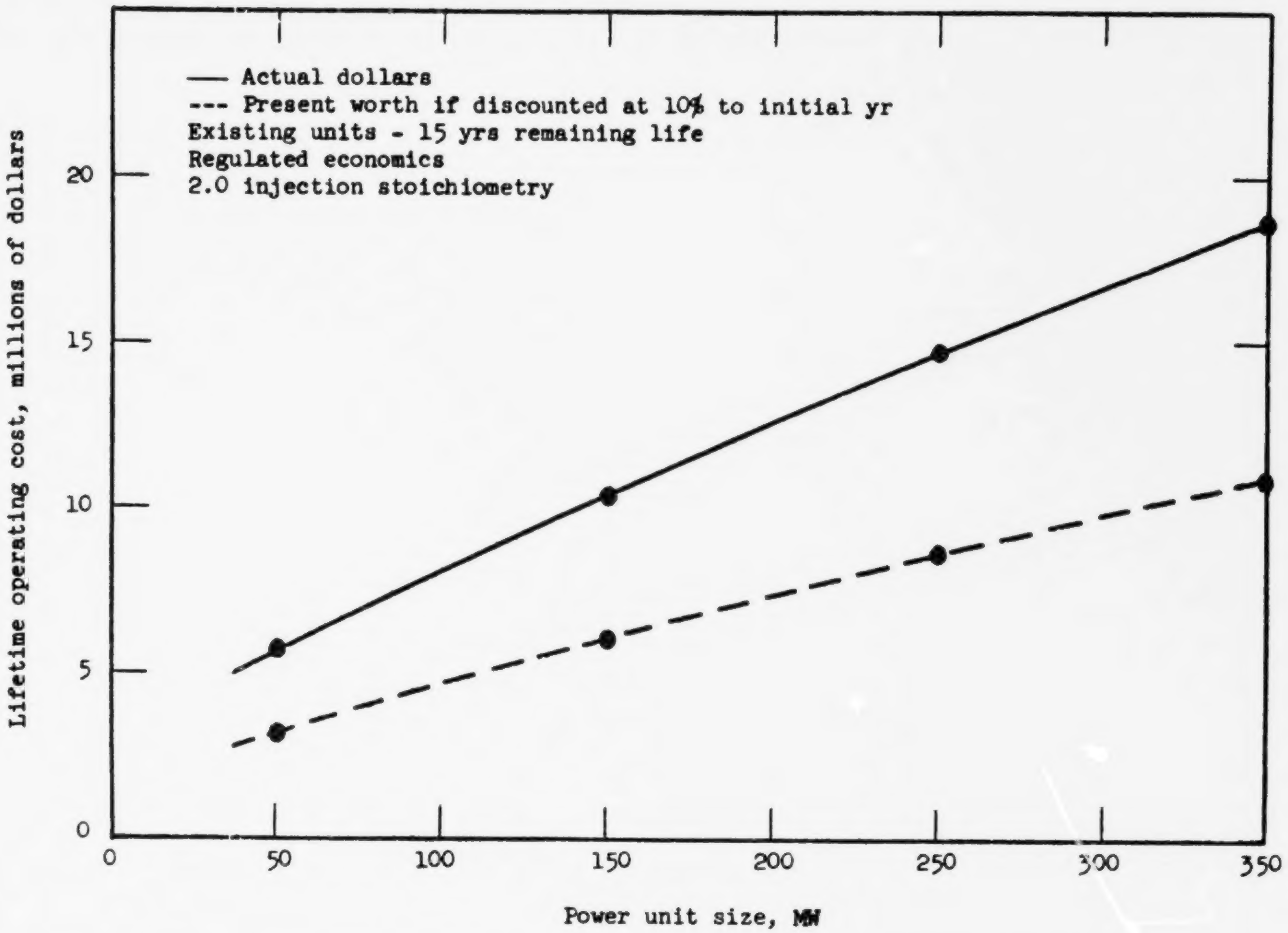

Figure 24. Effect of Power Unit Size and Injection Stoichiometry on Lifetime Increase in Cost of Power Using Dry Limestone Injection: 3.0% S Coal

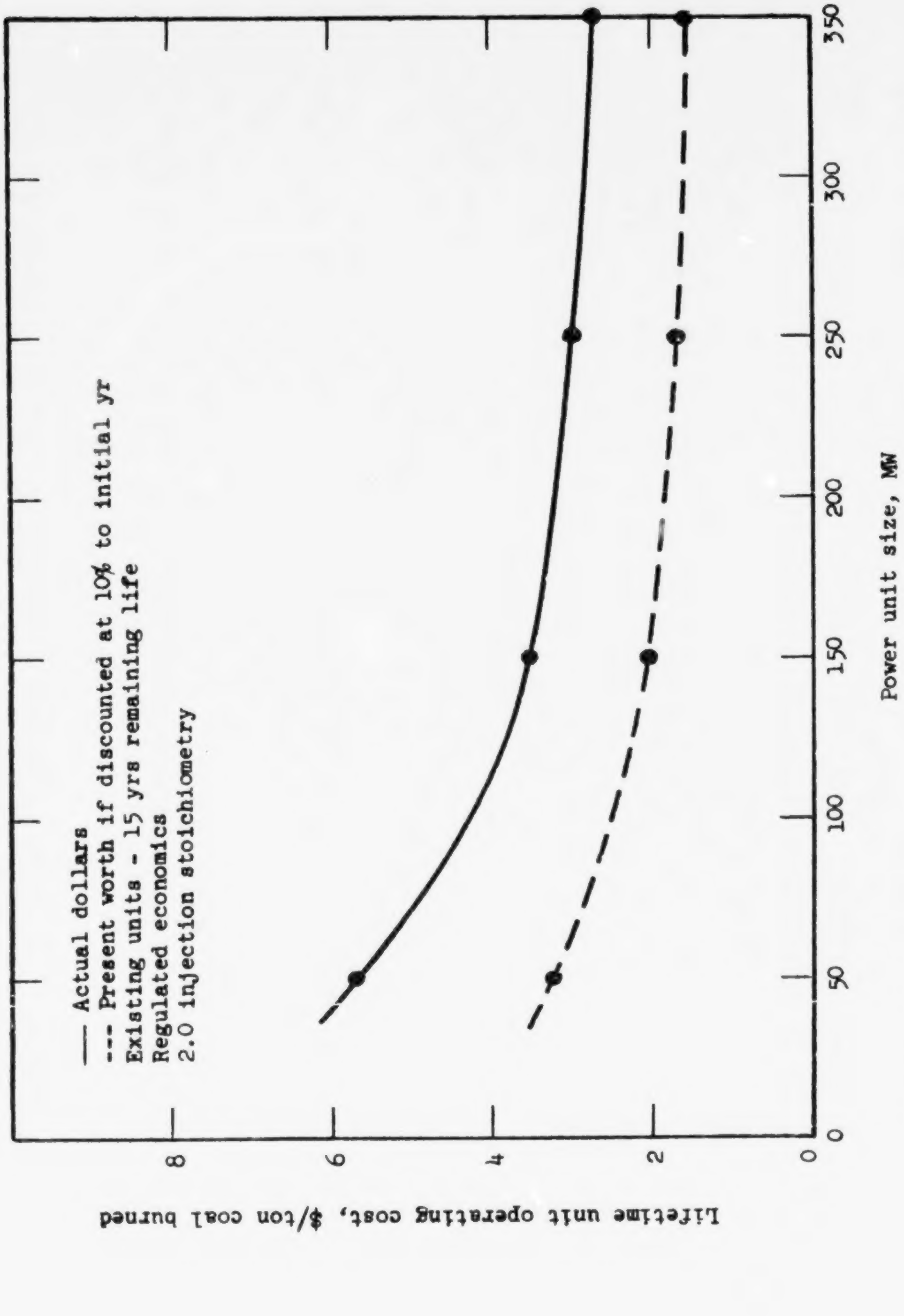

Figure 25. Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Coal Burned Over Life of Plant: 3.0% S Coal

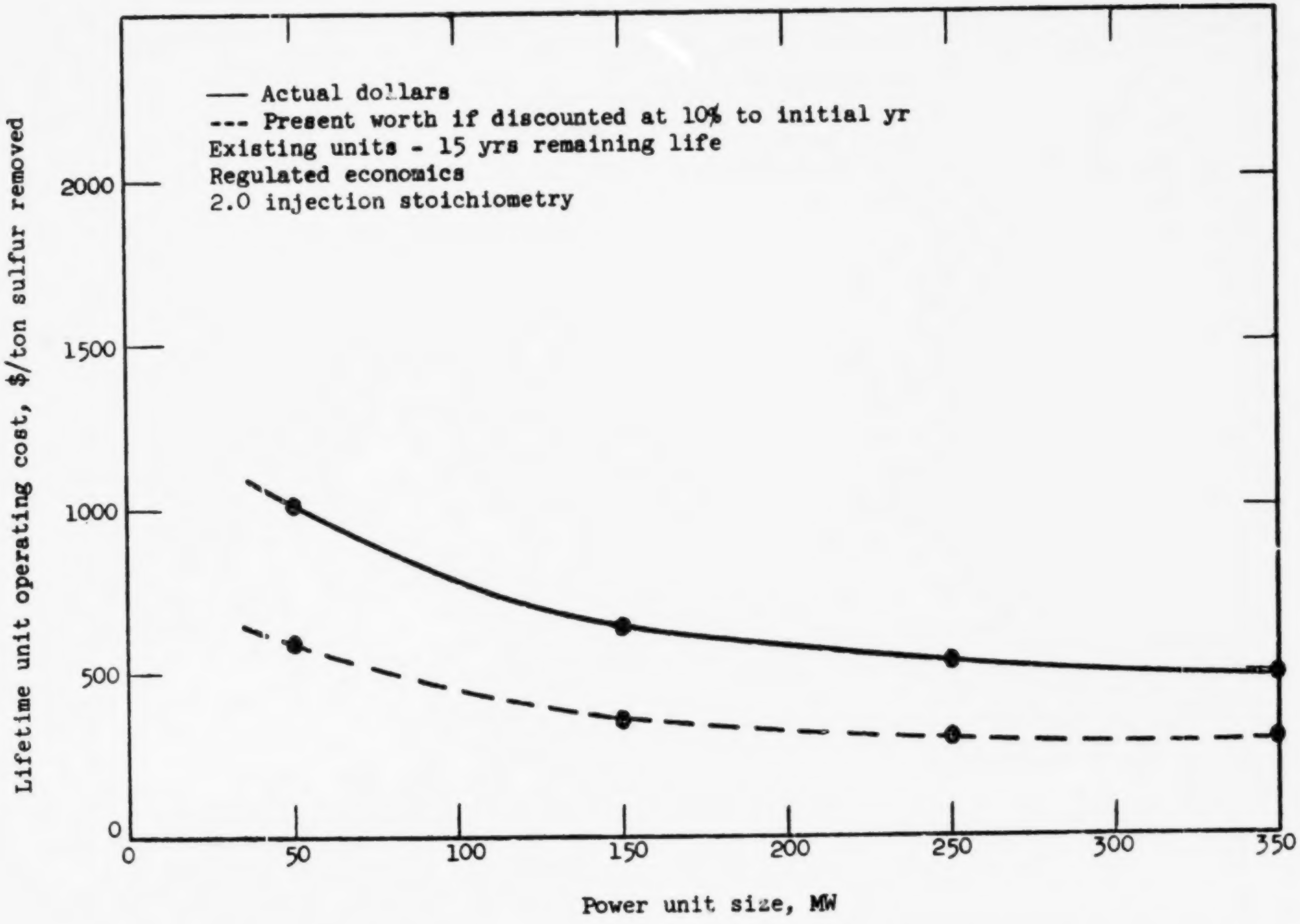

Figure 26. Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Sulfur Removed Over Life of Plant: 3.0% S Coal

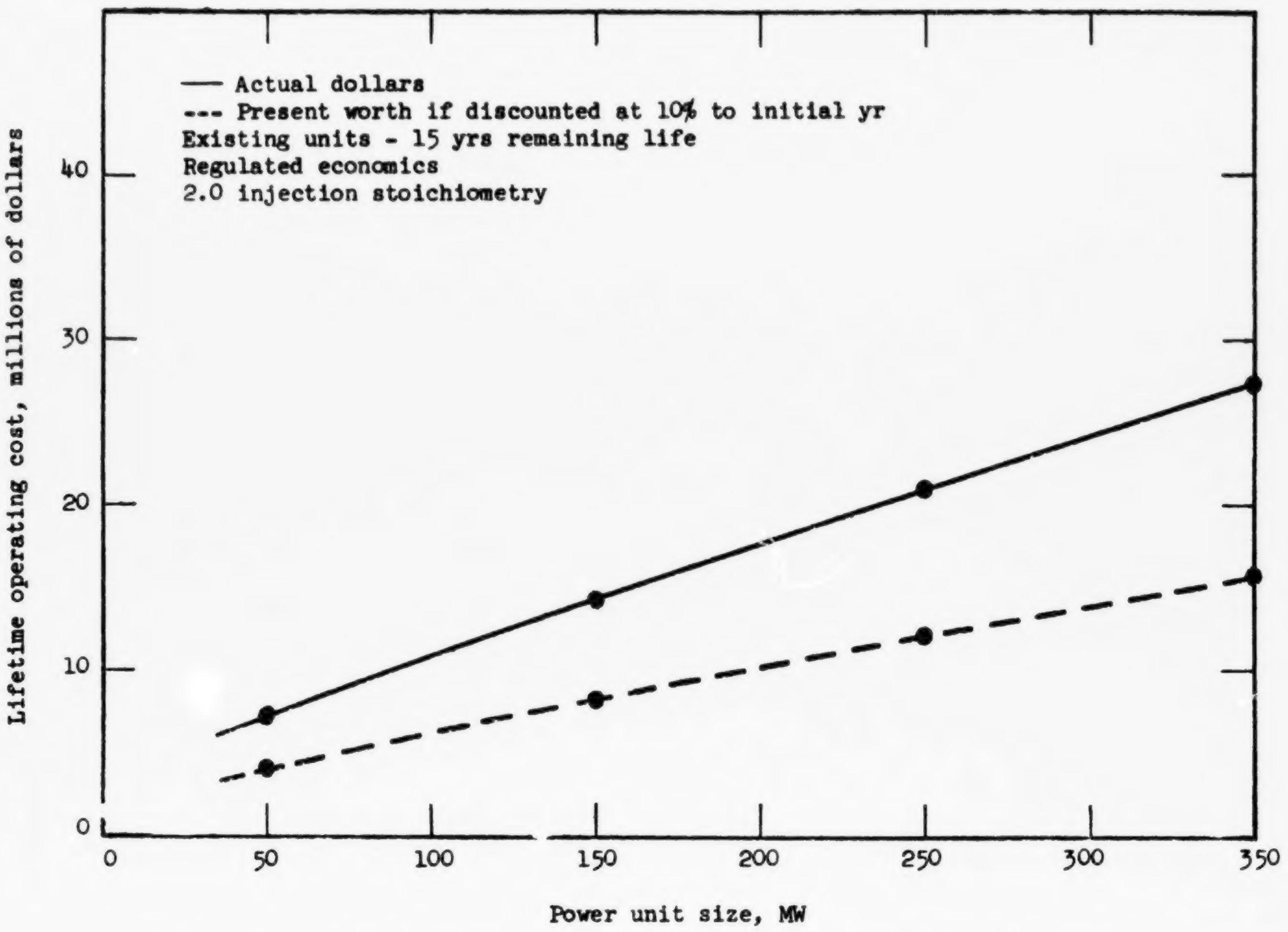

Figure 27. Effect of Power Unit Size and Injection Stoichiometry on Lifetime Increase in Cost of Power Using Dry Limestone Injection: 5.0% S Coal

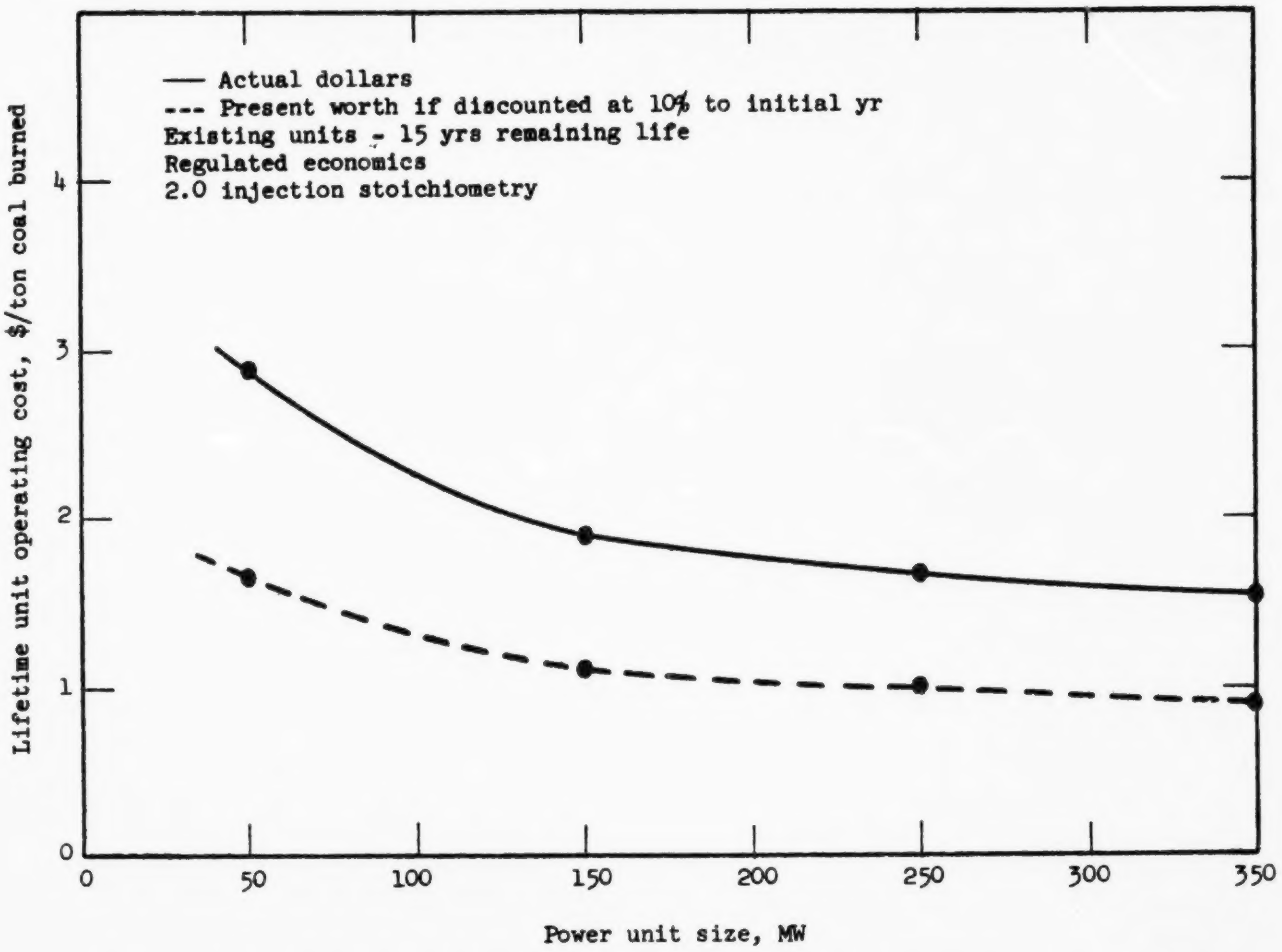

Figure 28. Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Coal Burned Over Life of Plant: 5.0% S Coal

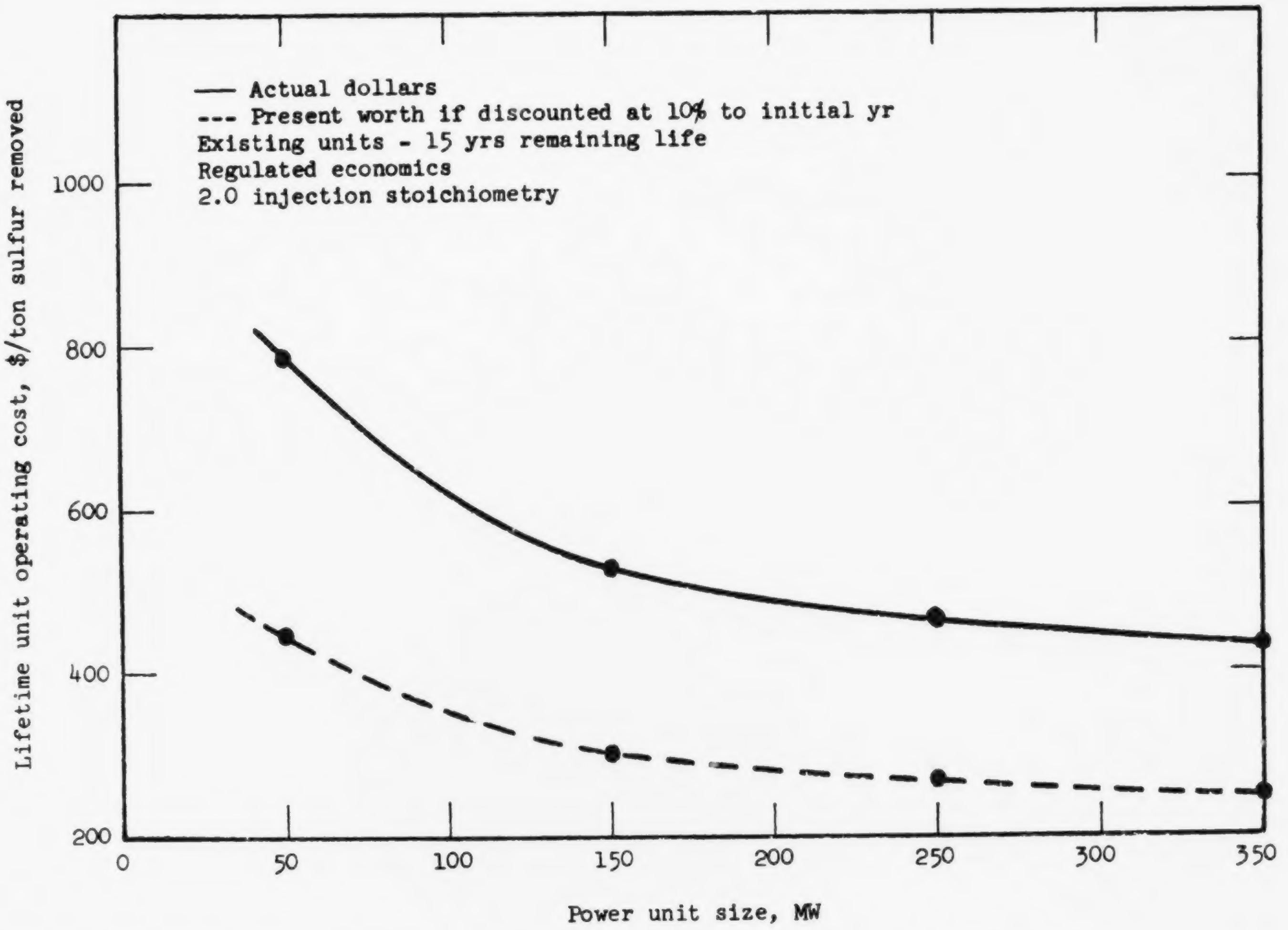

Figure 29 . Effect of Power Unit Size and Injection Stoichiometry on Dry Limestone Process Operating Cost Per Ton of Sulfur Removed Over Life of Plant: 5.0% S Coal

Results of Sensitivity Analyses

Sensitivities of the dry limestone injection process investment and operating costs to variations in several of the major factors are discussed below.

1. Sootblowers—The effect of additional sootblower requirements on total fixed capital investment for the three base case installations is shown in table 16. For these projections, a total installed cost of $40,000 each including indirect costs was utilized. These results indicate that total investment requirements are increased less than 10% with installation of up to four additional sooblowers. Although total operating costs were not established, capital charges account for an increase in annual operating costs of approximately $7,000 for each.

2. Particle size of injected limestone—The dry grinding and classifying equipment at Shawnee were designed and operated at various limestone size reduction capabilities so the effect of particle size on SO_2 removal could be determined. Two levels of grind, 80% - 400 mesh and 50% - 400 mesh, were given greatest attention. Although the Shawnee data was limited and is not totally conclusive, directional results of these and other investigations indicate that increased SO_2 removal efficiencies are obtained with injection of finer ground limestone. To determine the sensitivity of limestone particle size on process economics, investment and operating cost data for three levels of grind at various throughput capacities were established (2). Results shown in figure 30 indicate that the investment required for grinding to 80% - 400 mesh is about 35-40% greater than that required for grinding to 80% - 200 mesh; however, the higher grinding capability increases total process investment approximately 7-10%.

Operating cost results shown in figures 31 and 32 indicate that overall grinding costs are approximately 25-30% higher for the fine grind facilities. The effect of higher levels of grind on overall process costs is realtively small because grinding costs are only 5-6% of the total operating cost.

It should be noted that, based on the limited Shawnee data using stones of varying hardness, grindability is not a significant cost factor.

3. Particulate removal alternatives—The particulate collection facilities on Shawnee unit 10 consist of a 65% effective mechanical collector followed by a 90% effective electrostatic precipitator. This system which has an overall fly ash collection efficiency of 97% was designed, installed, and placed into operation prior to installation of the dry limestone injection process.

Additional solids collection capacity was not installed for the injection tests; however, performance data with and without dry limestone injection were derived for estimating incremental requirements and costs.

Although EPA has not promulgated particulate emission standards for existing power units, many states and local governing bodies have. In many cases, particulate removal efficiencies greater than 97% are required. For the lack of a better basis, it is assumed that these regulations will require plants utilizing dry limestone injection to maintain particulate emissions at a level equivalent to that obtained prior to installation of

Table 16

Effect of Additional Sootblower Requirements on Total Fixed Capital Investment: 150 MW Power Units

No. of additional sootblowers required	Power unit installation					
	0.8 %S - 5.0 stoichiometry		3.0% S - 2.0 stoichiometry		5.0% S - 2.0 stoichiometry	
	Total process investment	Sootblower cost sensitivity, % of total investment	Total process investment	Sootblower cost sensitivity, % of total investment	Total process investment	Sootblower cost sensitivity, % of total investment
0	1,568,800	0.0	1,874,200	0.0	2,369,500	0.0
1	1,608,800	2.5	1,914,200	2.1	2,409,500	1.7
2	1,648,800	4.9	1,954,200	4.1	2,449,500	3.3
3	1,688,800	7.1	1,994,200	6.0	2,489,500	4.8
4	1,728,800	9.3	2,034,200	7.9	2,529,500	6.3

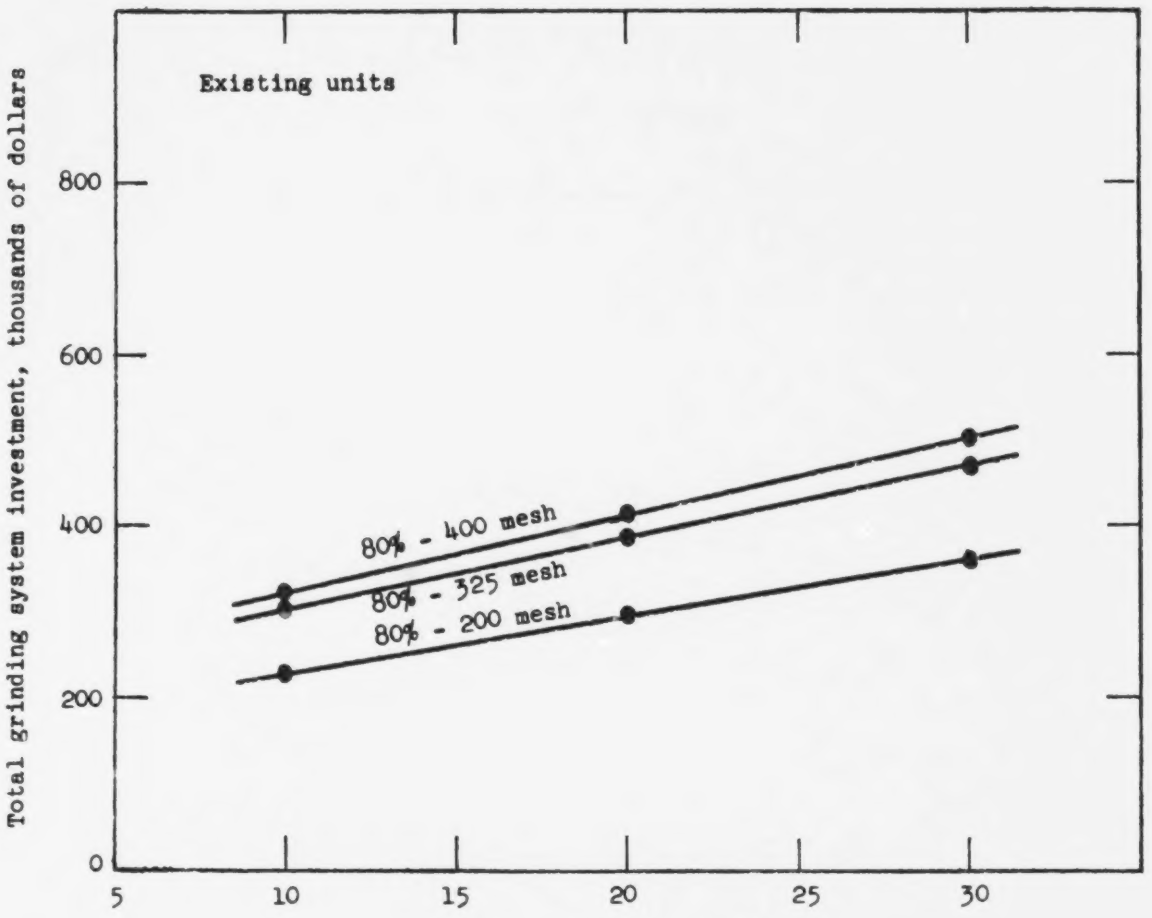

Figure 30. Effect of Limestone Grinding Capacity and Fineness of Grind on Total Grinding System Investment: Dry Limestone Injection Process

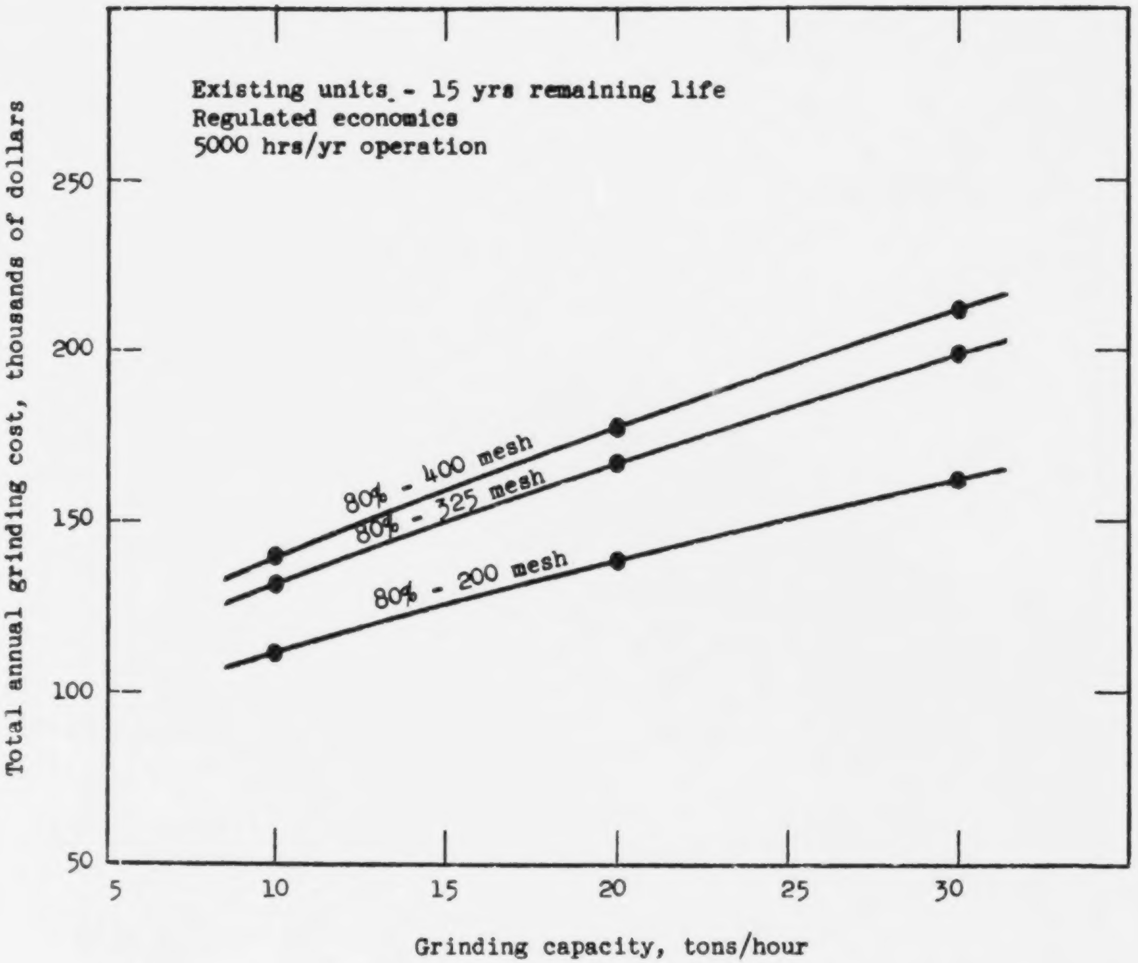

Figure 31 . Effect of Limestone Grinding Capacity and Fineness of Grind on Annual Operating Cost for Grinding: Dry Limestone Injection Process

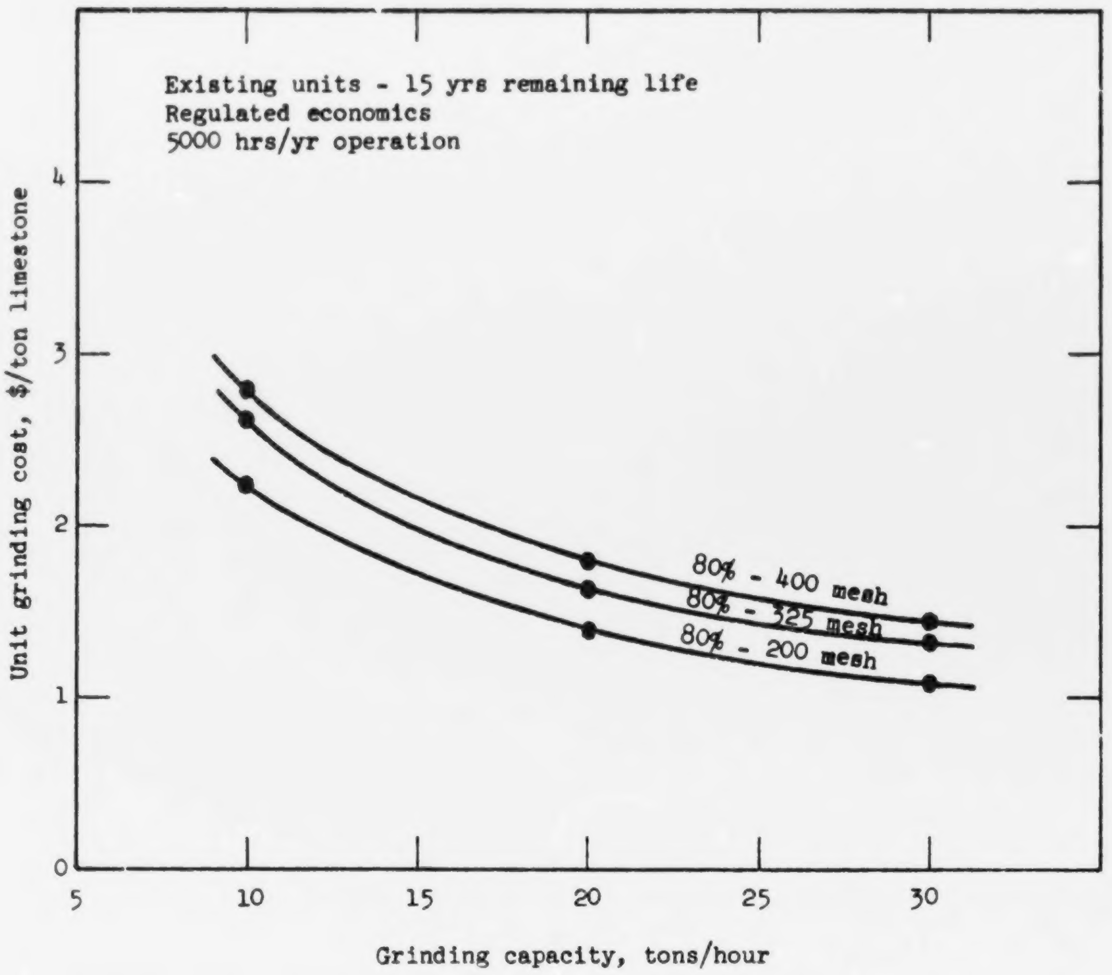

Figure 32. Effect of Limestone Grinding Capacity and Fineness of Grind on Unit Grinding Cost: Dry Limestone Injection Process

the process. For consistency in the evaluation, a dust removal efficiency of 99% prior to injection or an outlet grain emission of 0.03 gr/acf is assumed.

From their study of electrostatic precipitator performance during the Shawnee Dry Limestone Injection test program, Cottrell Environmental Systems, Inc.[1] reported five separate alternatives which may be considered for design of additional dust collection facilities, including:

1. Size modification of the presently installed dust collecting system.
2. Installation of a "hot" precipitator.
3. Gas cooling ahead of the dust collecting system (in conjunction with size modification).
4. Gas conditioning ahead of the dust collecting system (in conjunction with size modification).
5. Electrical energization of the precipitator.

Based on their study, CES indicates that with gas cooling ahead of the dust collecting system (alternative 3), the least additional precipitator plate area might be required. Their results, however, do not include costs for gas cooling facilities, nor do they represent carefully researched data needed for design modifications of such a system. Since design requirements for the other alternatives are also speculative at this time, size modifications of the presently installed dust collecting system (alternative 1) is considered the most practical method for meeting additional dust removal requirements for existing power plants. The Shawnee test data were used by Cottrell Environmental Systems, Inc., to estimate incremental precipitator investment requirements based on increasing the precipitator plate area for a 150 MW unit with any one of the following four combinations of dust collectors prior to limestone injection:

Dust collector type	Overall fly ash collection efficiency prior to injection, %
1. No collection devices	0
2. Mechanical collector	65
3. Electrostatic collector	99
4. Mechanical and electrostatic collectors in series	99

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[1] Brown, R. F. "Report and Analysis of Field Tests at Shawnee Station of TVA, Including a Techno-Economic Evaluation of Options for Maintaining the Stack Emission Rate with Limestone Injection Equivalent to a Baseline of No Limestone Injection." Final draft prepared by Cottrell Environmental Systems, Inc., for the Environmental Protection Agency, Contract No. CPA 22-69-139, Particulates Collection Study, TVA Dry Limestone Tests. October 31, 1972.

Assuming a final outlet grain loading of 0.03 gr/acf after injection for each sulfur content and stoichiometry, the estimated fixed investment requirements are tabulated in table 17 and are shown graphically in figures 33 through 36 for the various combinations of existing collection facilities. Depending on the dust removal capability existing prior to injection, incremental dust collection investment could cover a wide range, as much as 2.4 times that projected in the case study (mechanical and electrostatic in series). Assuming no collection devices existing prior to injection, total process investment could be approximately 28% higher than estimated in the parametric evaluation.

4. Disposal costs—In the 52-case parametric study, additional pond facilities were not provided since the availability and cost of additional space depends upon the actual plant location. In many cases, some additional disposal area will be necessary, and these additional investment costs should be added to the dry limestone injection process investment.

Figure 37 shows the relationship between the incremental annual disposal burden and the projected pond disposal costs incorporated in the parametric study. As this figure indicates, the projected disposal expense decreases with increasing solids disposal burden to a cost less than $0.50/ton of solids. For the three base cases, these costs range from 4.6 to 5.1% of the total process operating cost. As an indication of the effect of higher disposal costs, a charge of $2.00/ton of solids would result in overall disposal costs ranging from 7 to 15% of the projected annual operating costs for these cases.

5. Raw material costs—Since limestone cost is one of the major operating expenses, the sensitivity of price on annual operating cost was determined. Figure 38 shows the effect of injection stoichiometry and delivered limestone price on the annual and unit operating costs for a 150 MW, 3.0% S coal-fired installation. At a stoichiometry of 4.0, a $2.00 change in the price of limestone results in a 20-30% change in annual costs.

The effect of power unit size and delivered limestone price on annual and unit operating costs for the process are shown in figures 39 and 40.

Table 17

Incremental Electrostatic Precipitator Invesetment[a] Required to Maintain Outlet Particulate Loading of 0.03 gr/acf on 150 MW Power Units Utilizing Dry Limestone Injection

		Incremental electrostatic precipitator costs, thousands of dollars, for power units equipped with the following existing dust collection facilities[a]			
Sulfur in coal, %[b]	Injection stoichiometry, moles CaO injected per mole sulfur in coal	None	65% Eff. Mechanical collector	99% Eff. Electrostatic collector	99% Eff. Mechancial and electrostatic collectors in series
0.8	3.0	763	582	408	321
0.8	4.0	778	601	423	339
0.8	5.0	794	619	439	358
0.8	6.0	808	635	453	373
0.8	7.0	824	648	469	386
3.0	1.0	790	606	435	345
3.0	2.0	843	666	488	405
3.0	3.0	886	716	531	454
3.0	4.0	924	753	569	491
5.0	1.0	831	653	476	392
5.0	2.0	905	734	550	473
5.0	3.0	967	797	612	535
5.0	4.0	1021	852	666	591

a. Including indirects
b. Assumes coal with 16% ash

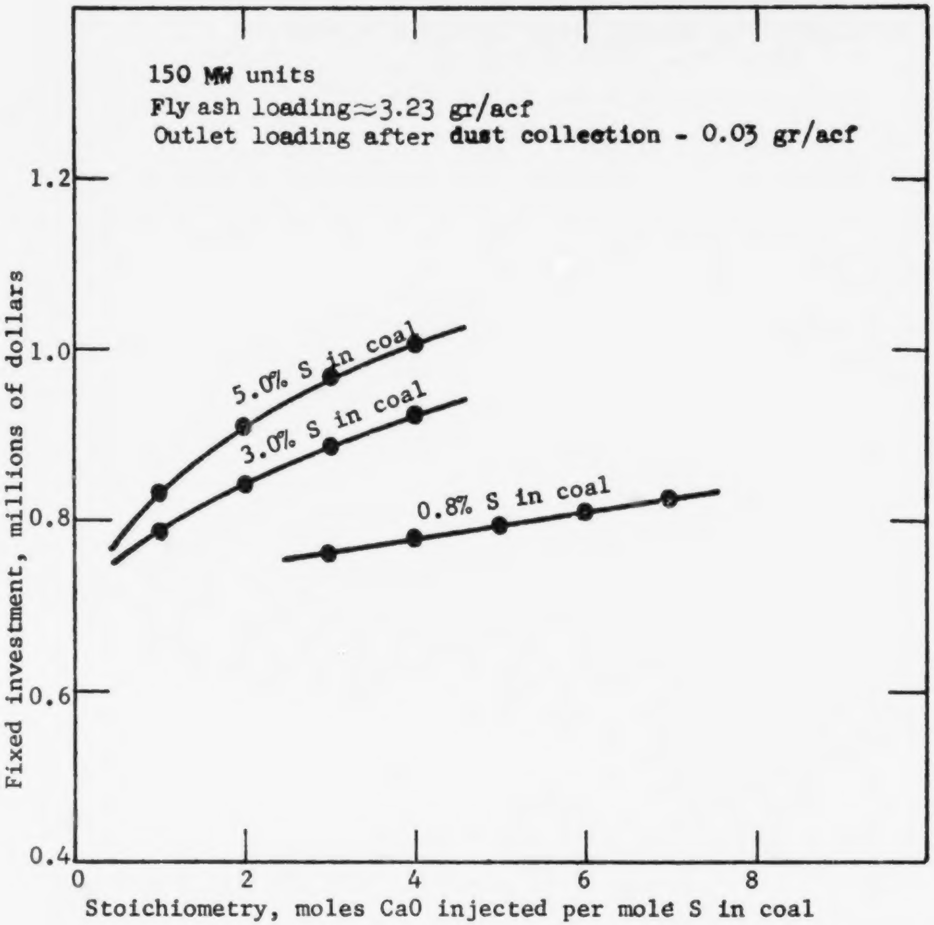

Figure 33 . Investment Requirements for Adding Incremental Electrostatic Precipitator to Power Plant without Collectors: Dry Limestone Injection Process

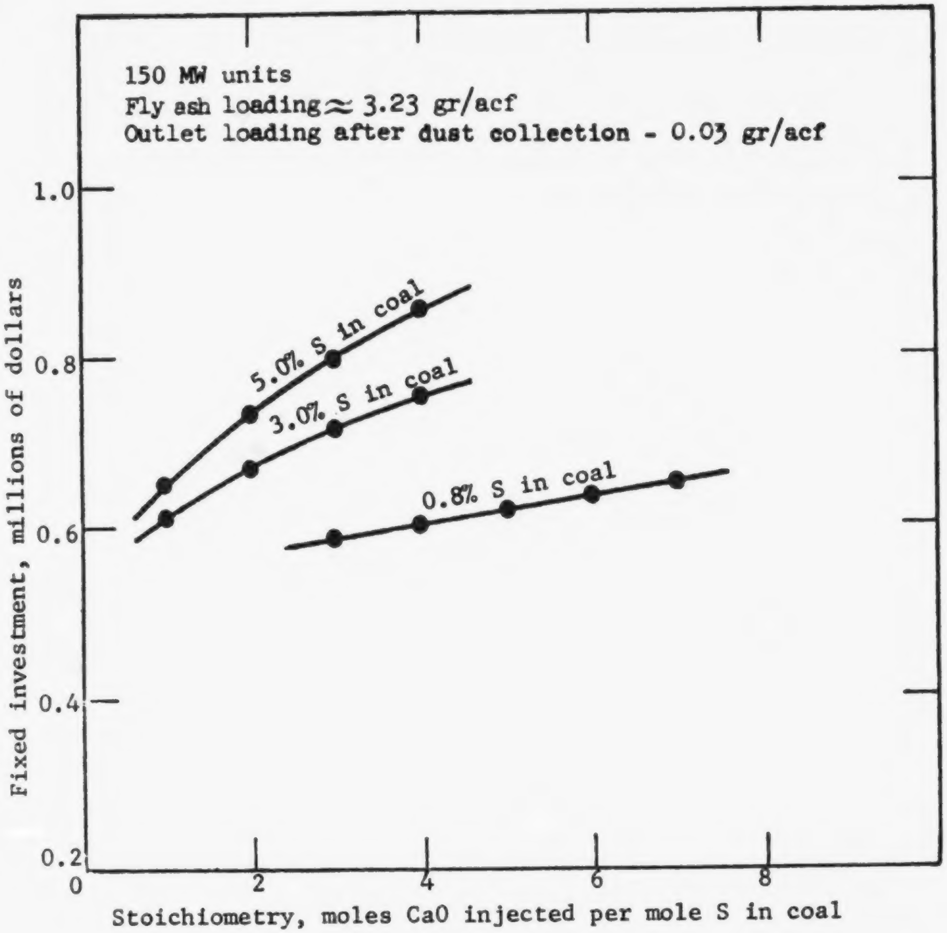

Figure 34. Investment Requirements for Adding Incremental Electrostatic Precipitator to Power Plant Having Existing 65% Effective Mechanical Collectors: Dry Limestone Injection Process

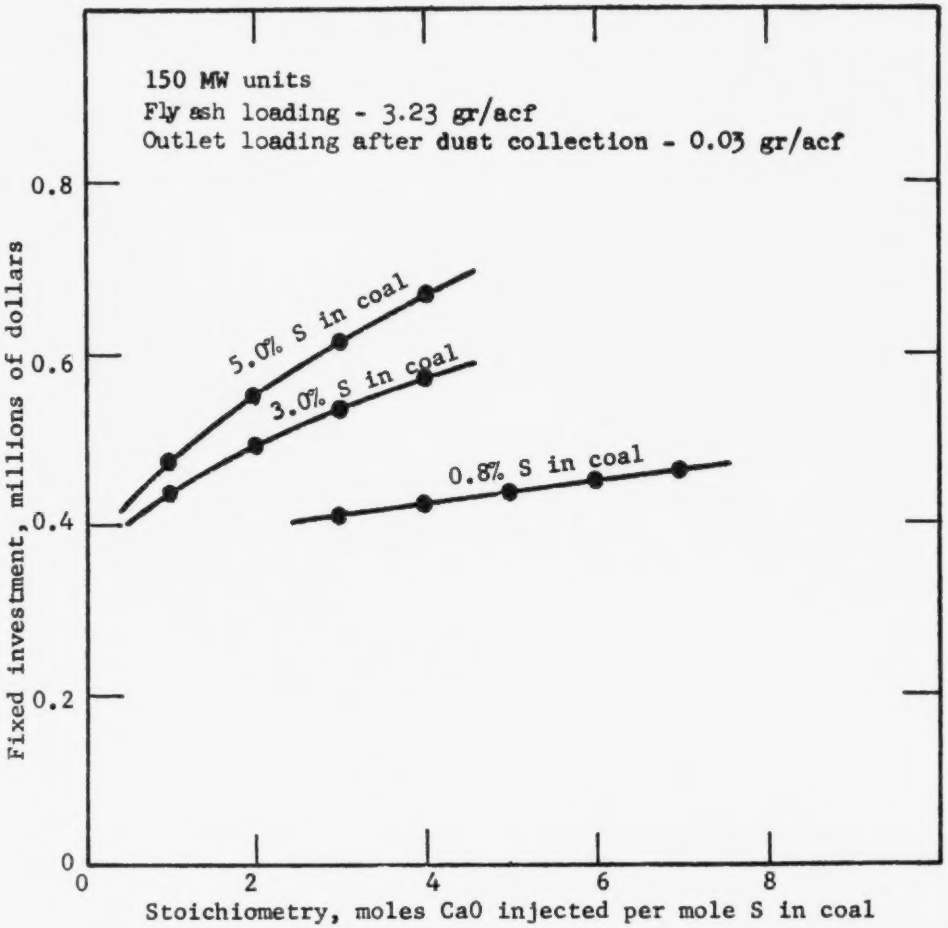

Figure 35. Investment Requirements for Adding Incremental Electrostatic Precipitator to Power Plant Having an Existing 99% Effective Precipitator: Dry Limestone Injection Process

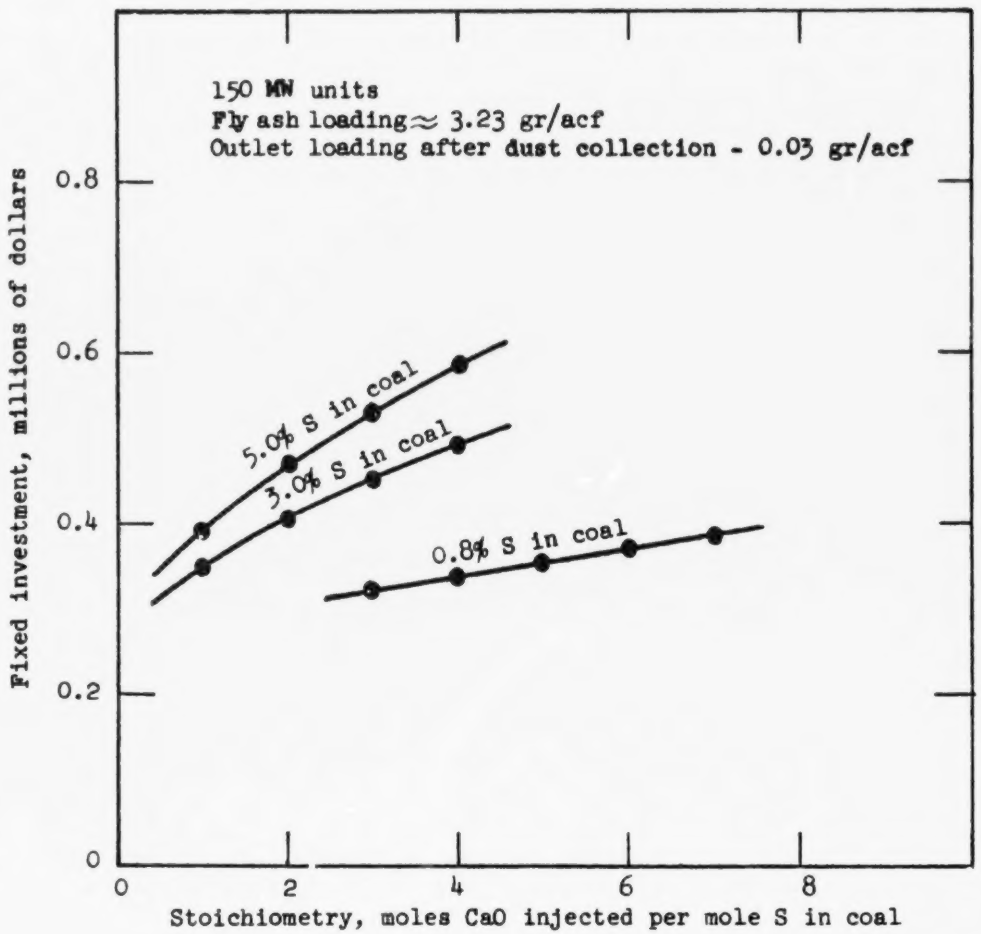

Figure 36. Investment Requirements for Adding Incremental Electrostatic Precipitator to Power Plant Having an Existing 99% Effective Combination of Mechanical and Electrostatic Collectors: Dry Limestone Injection Process

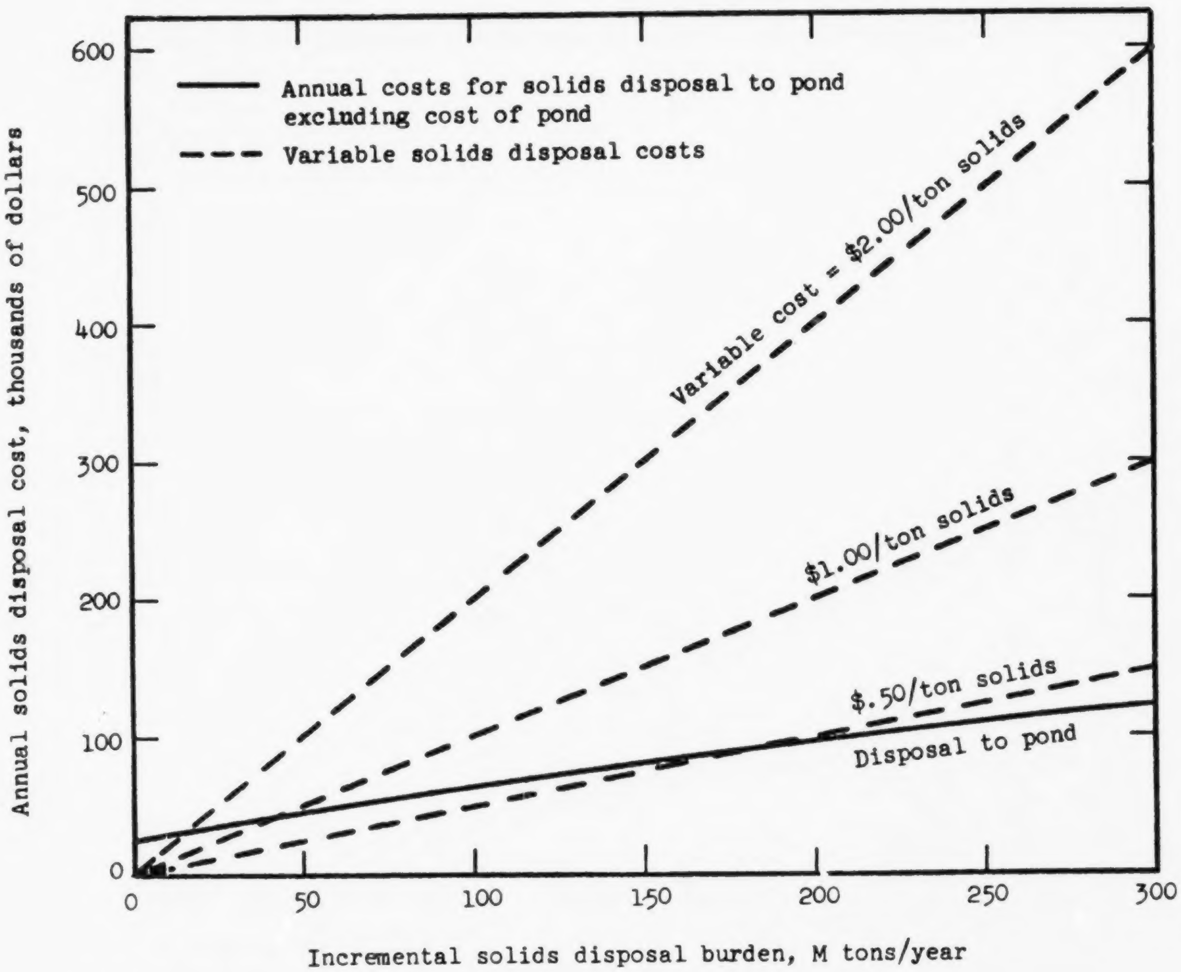

Figure 37 . Effect of Incremental Solids Disposal Burden on Annual Disposal Cost for Dry Limestone Injection Solids

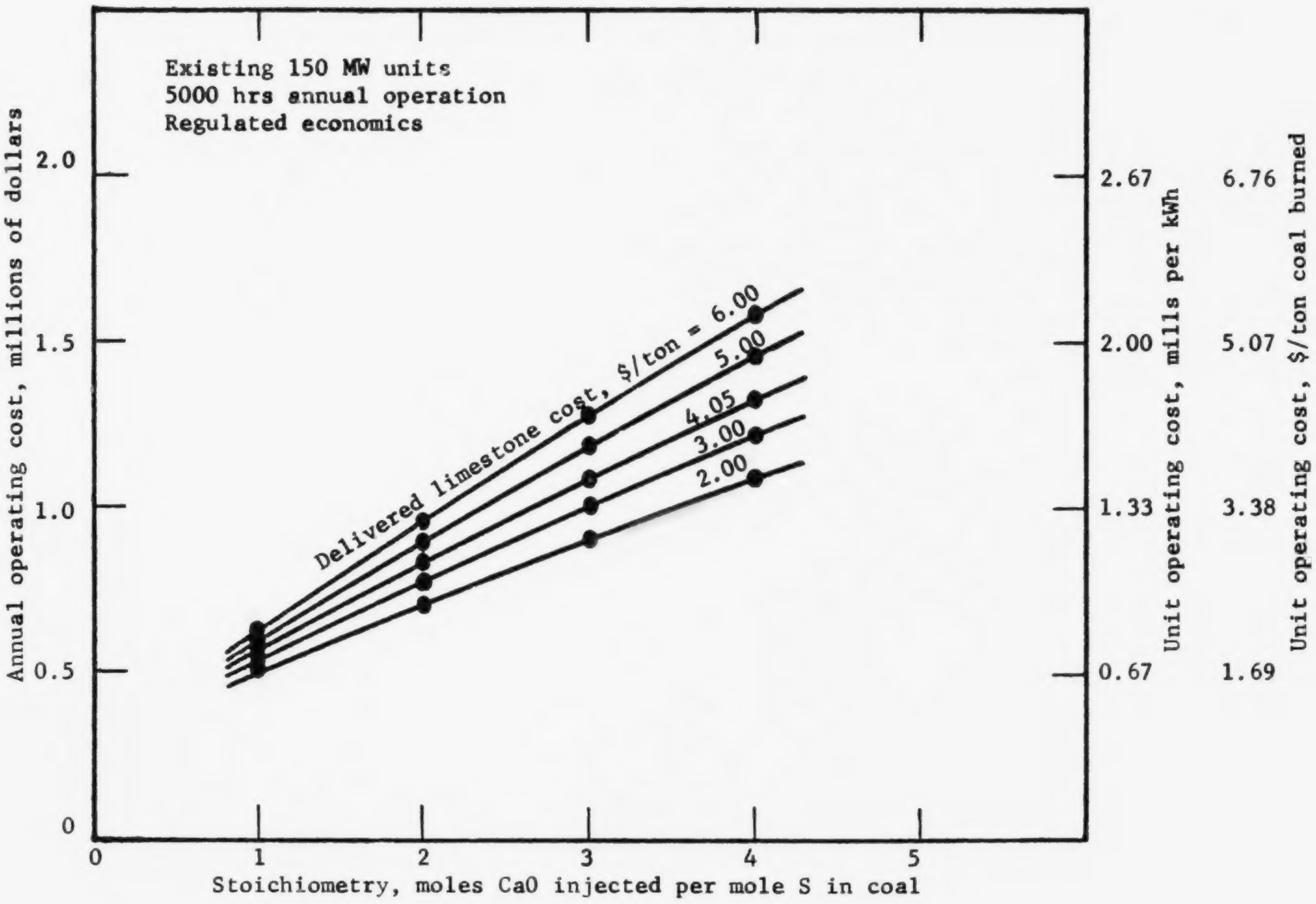

Figure 38. Effect of Injection Stoichiometry and Delivered Limestone Cost on Annual and Unit Operating Cost for Dry Limestone Process: 3.0% S Coal

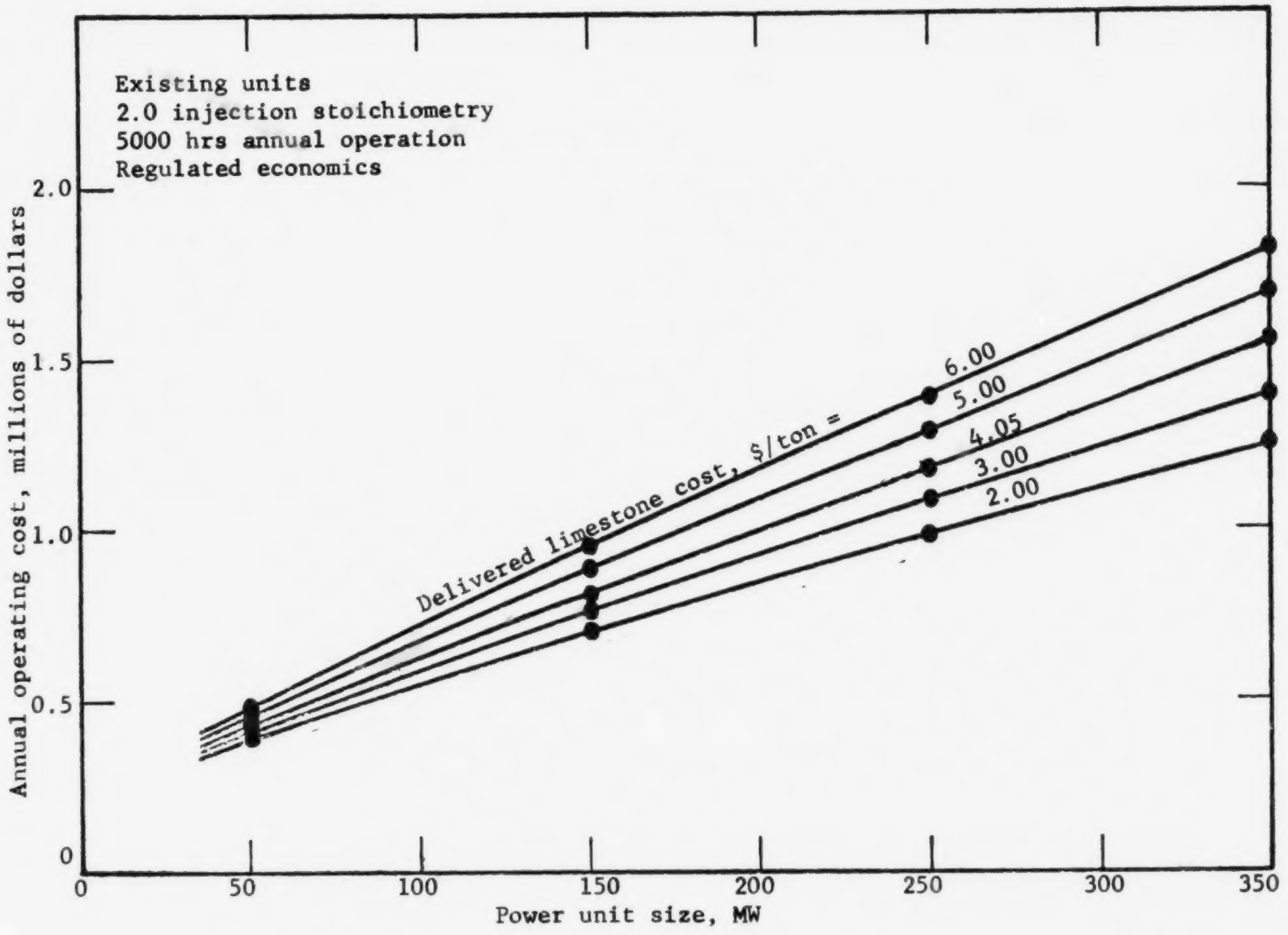

Figure 39. Effect of Power Unit Size and Delivered Limestone Cost on Annual Operating Cost for Dry Limestone Injection Process: 3.0% S Coal

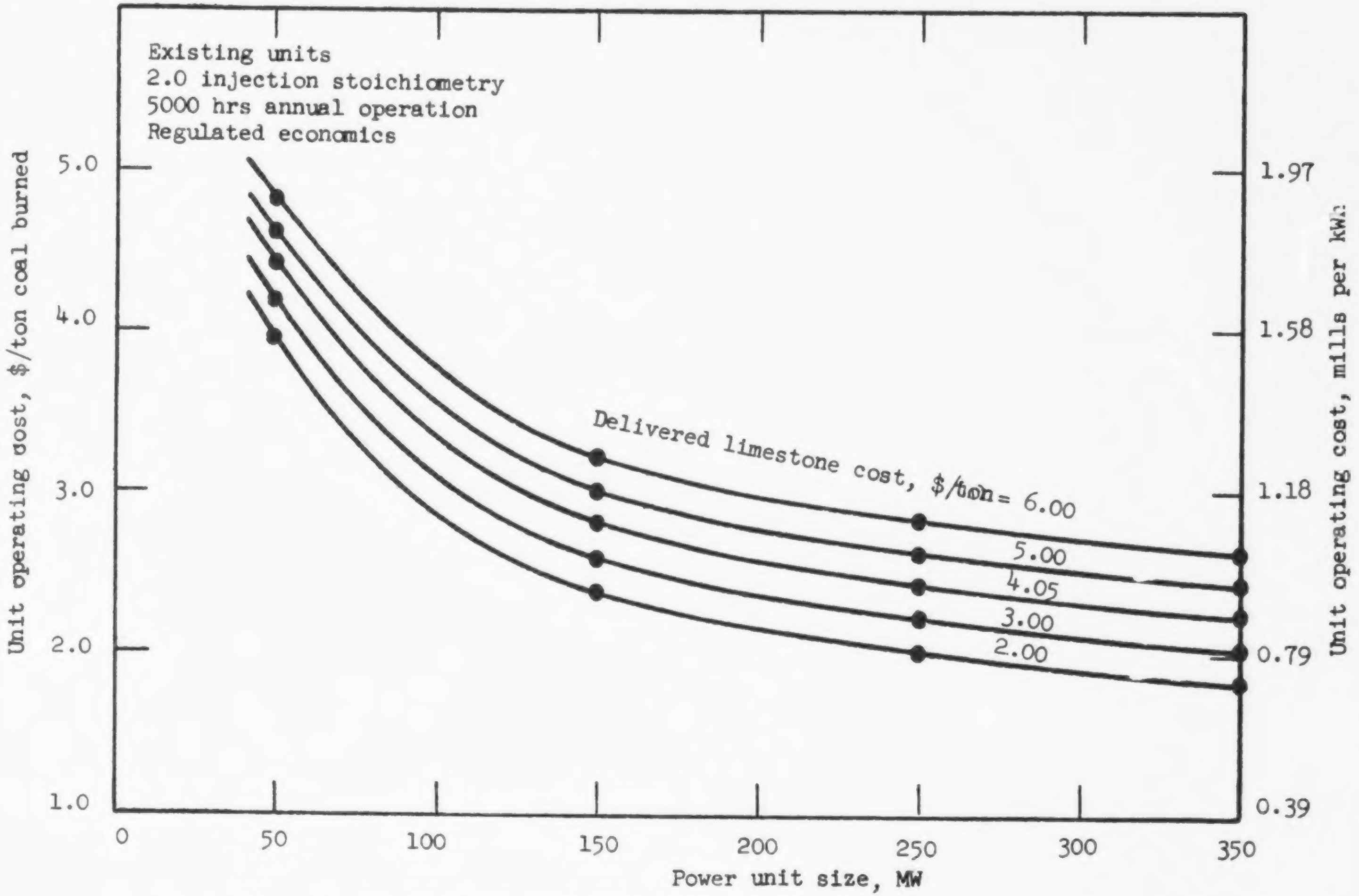

Figure 40. Effect of Power Unit Size and Delivered Limestone Cost on Dry Limestone Process Unit Operating Cost: 3.0% S Coal

6. Annual on-stream time—The effect of variations in process on-stream time on annual operating costs are shown in figure 41 for three plant sizes at various sulfur levels of fuel. As illustrated, the cost effect is much more pronounced for large plants using high sulfur coal. Figure 42 shows the effect of on-stream time on unit operating costs per ton of sulfur removed. These unit operating costs decrease with increased on-stream time and are much higher for the low MW and low sulfur applications. This result is partially the effect of greater economy of scale for operating the larger installations; however, the largest factor is the reduced SO_2 absorption efficiency attained for low sulfur coal.

7. Operation at half load—In the dry limestone injection test program, higher sulfur dioxide removal efficiencies were observed during operation of the power unit at half load. To determine the effect of these higher efficiencies on unit operating costs, projections are made for a 150 MW unit operating at full and half load assuming various annual on-stream hours. The resulting unit operating costs are shown in figures 43 and 44. Although approximately 50% lower operating costs per ton of sulfur removed are projected at reduced load, the costs per ton of coal burned are about the same. The operational costs at half load do not include a charge for power generating capacity intentionally idled to increase absorption which, if assessed, would make half-load operation more costly per unit of electricity generated.

8. Remaining life of plant—figures 45 through 47 show the effect of remaining life of the power plant on lifetime total and unit operating costs for various megawatt sizes. Similar relationships indicating the effect of remaining life of power plant on lifetime total and unit operating costs for various sulfur levels are given in figures 48 through 50.

Although total operating costs increase as a result of greater operation, these results show that unit operating costs for power plants with 10 years remaining life are approximately half of similar unit costs for plants with 5 years remaining life. This result is attributed primarily to the increased annual capital charge rate resulting from operation for fewer years plus the difference in tons of coal burned or sulfur removed.

9. Labor cost escalation—To determine the effect of escalating labor rates on lifetime operating costs for dry limestone injection, projections assuming annual labor escalation rates varying from 0 to 10.0%/year were made. The results, presented in table 18 and figure 51, show that lifetime operating costs for dry limestone injection are not greatly increased as a result of labor cost escalation. Lifetime unit operating costs range from $3.53/ton of coal burned assuming no escalation to $3.95/ton at an escalation rate of 10%/year for the remaining 15-year life of the plant. At the higher escalation rate, lifetime costs are approximately 11.8% higher than projected costs excluding escalation.

Table 18

Effect of Annual Labor Escalation Rates on Lifetime Operating Cost for Dry Limestone Injection Process Under Regulated Economics - 150 MW Unit, 3.0% S in Coal, 2.0 Injection Stoichiometry [a]

Annual labor escalation rate %	Lifetime operating cost				Total increase in lifetime operating cost resulting from escalation, %	Cumulative present worth of net increase in cost of power discounted at 10%/yr			
	$	$/ton coal	mills/ kWh	$/ton S removed		$	$/ton coal	mills/ kWh	$/ton S removed
0	10,438,200	3.53	2.03	640	-	6,002,800	1.39	0.80	368
2.5	10,669,100	3.61	2.06	654	2.2	6,097,300	1.42	0.81	374
5.0	10,944,700	3.71	2.10	671	4.9	6,206,900	1.46	0.83	380
7.5	11,275,500	3.82	2.15	691	8.0	6,335,300	1.50	0.84	388
10.0	11,670,700	3.95	2.20	715	11.8	6,484,800	1.56	0.86	397

a. Existing units - 15 yrs. remaining life. Assumed operating profile:
5 yr at 5000 hr/yr
5 yr at 3500 hr/yr
5 yr at 1500 hr/yr

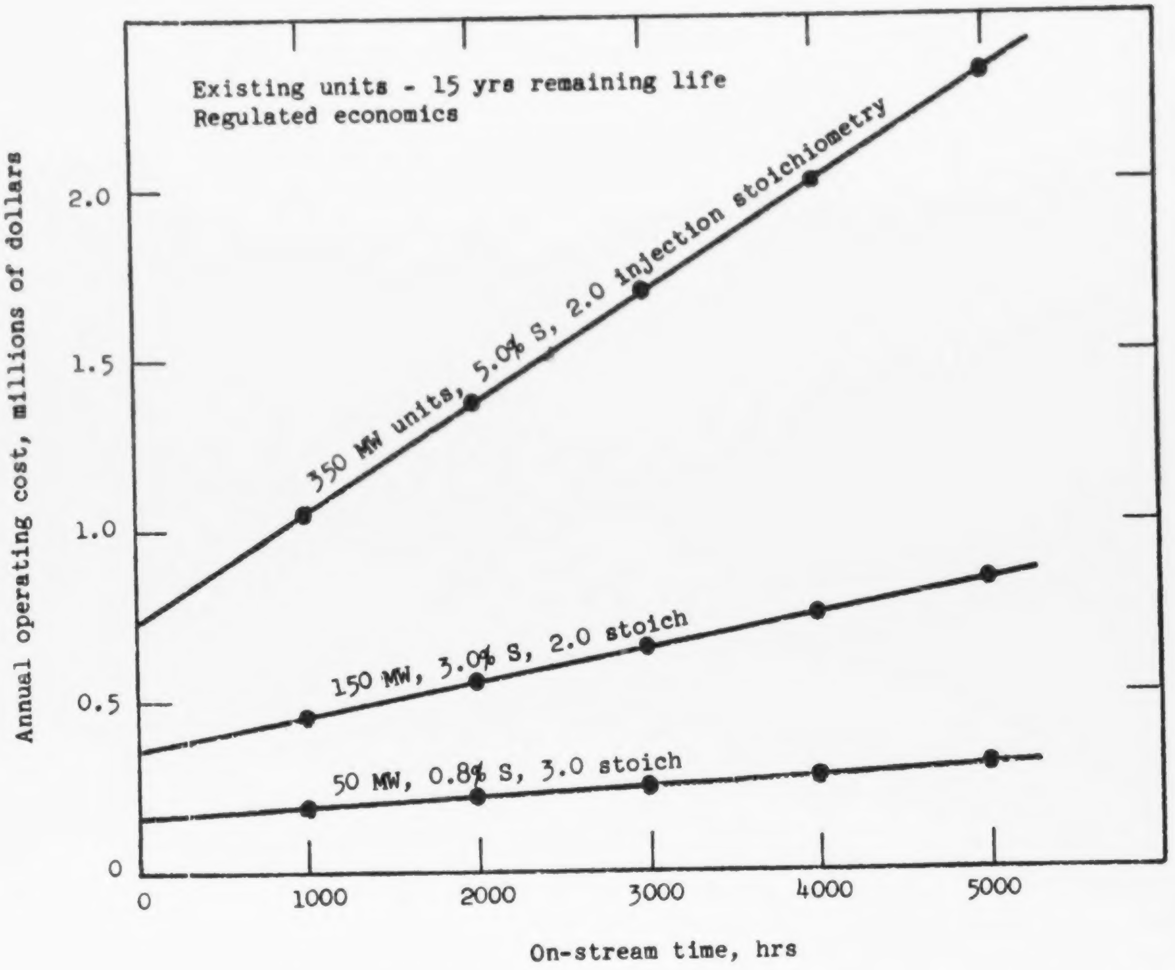

Figure 41 . Effect of Annual On-Stream Time at Full Load on Annual Operating Cost for Various Size Dry Limestone Injection Process Installations

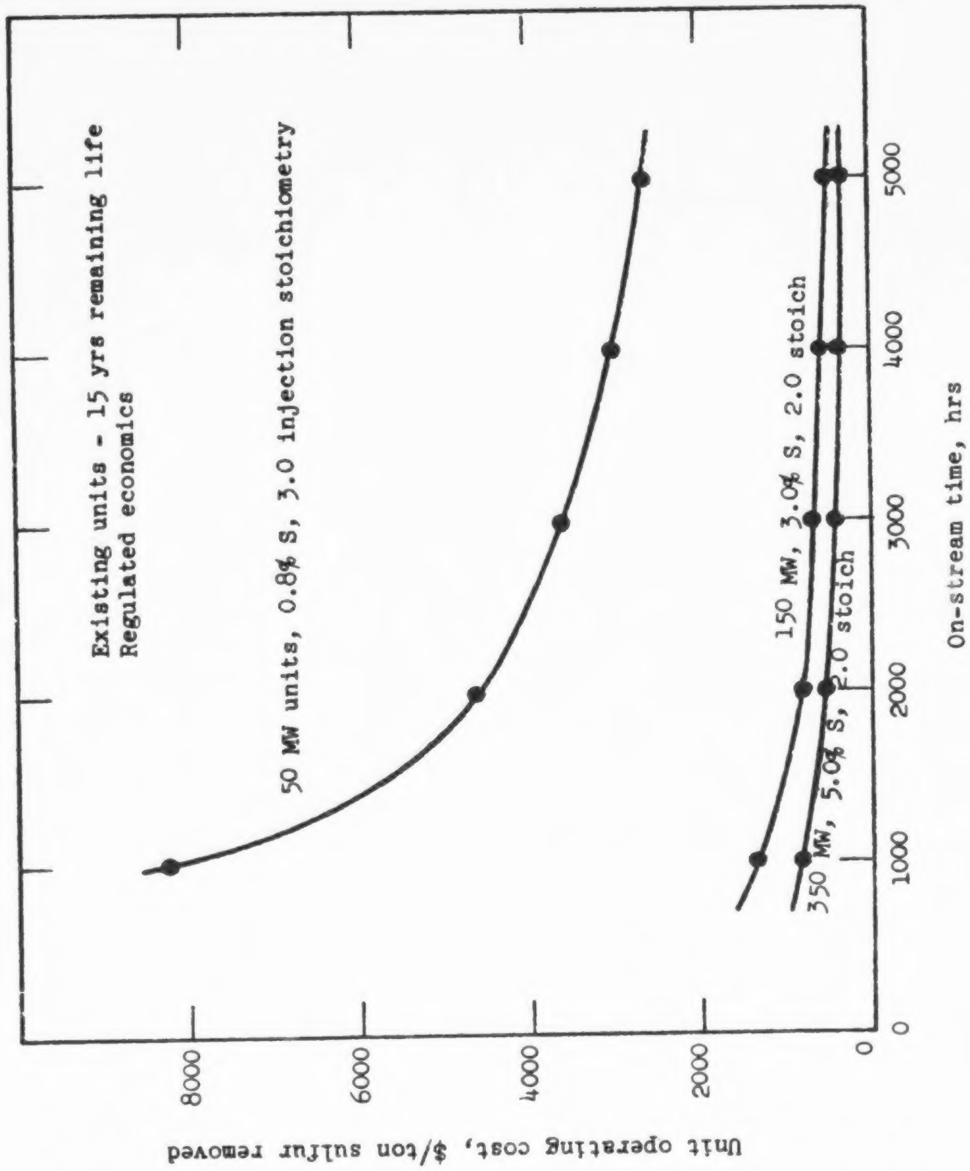

Figure 42. Effect of Annual On-Stream Time at Full Load on Unit Operating Cost Per Ton of Sulfur Removed for Various Size Dry Limestone Injection Process Installations

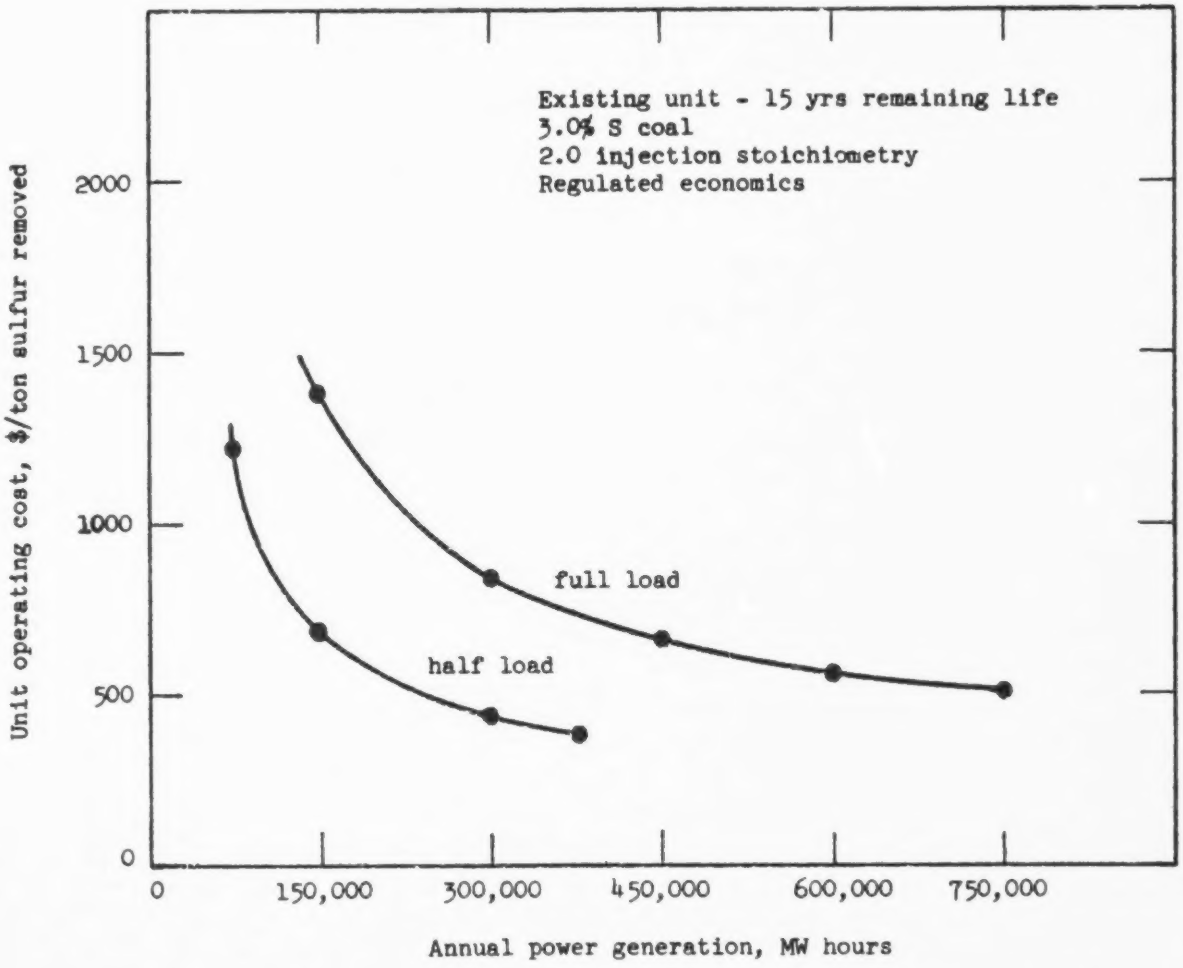

Figure 43. Effect of Annual Power Generation at Full and Half Load on Dry Limestone Process Unit Operating Cost Per Ton of Sulfur Removed: 150 MW Unit

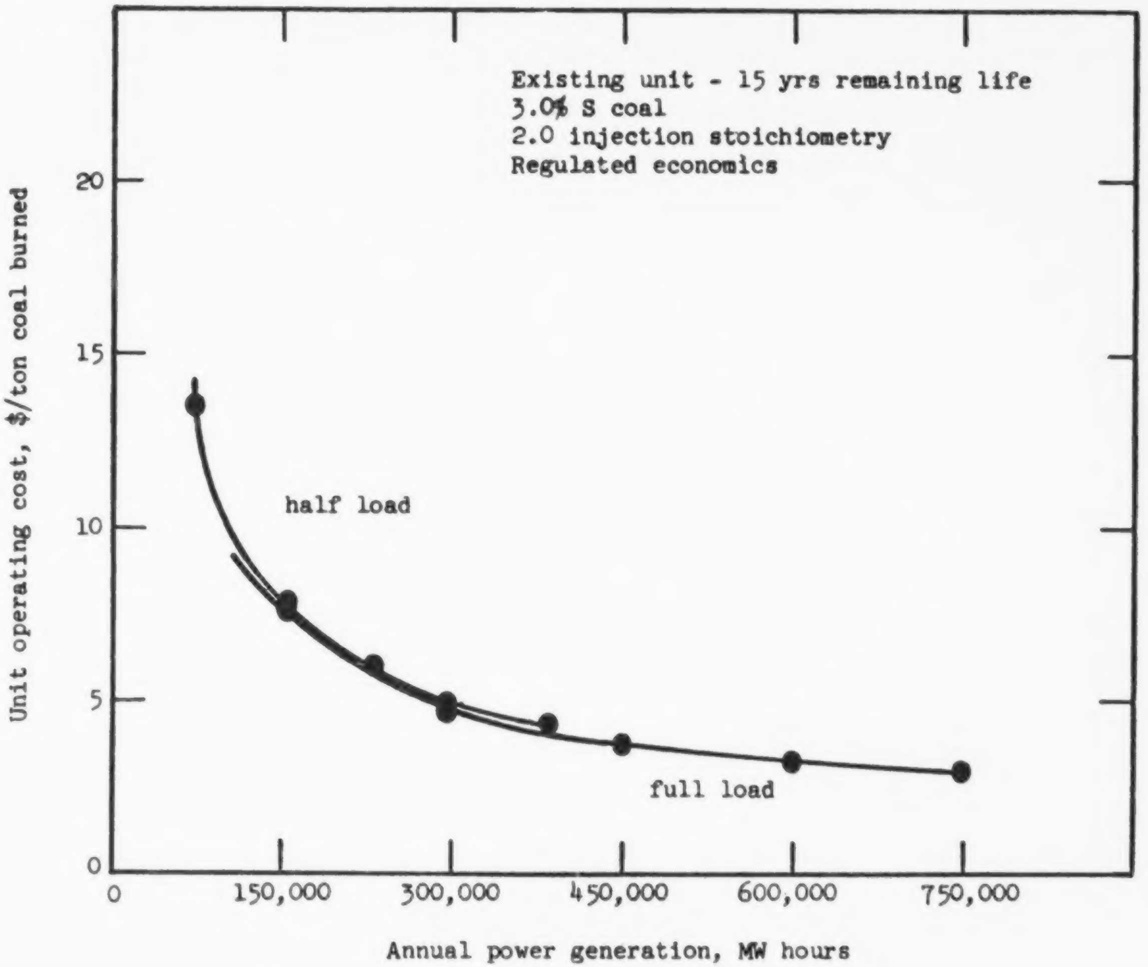

Figure 44. Effect of Annual Power Generation at Full and Half Load on Dry Limestone Process Unit Operating Cost Per Ton of Coal Burned: 150 MW Unit

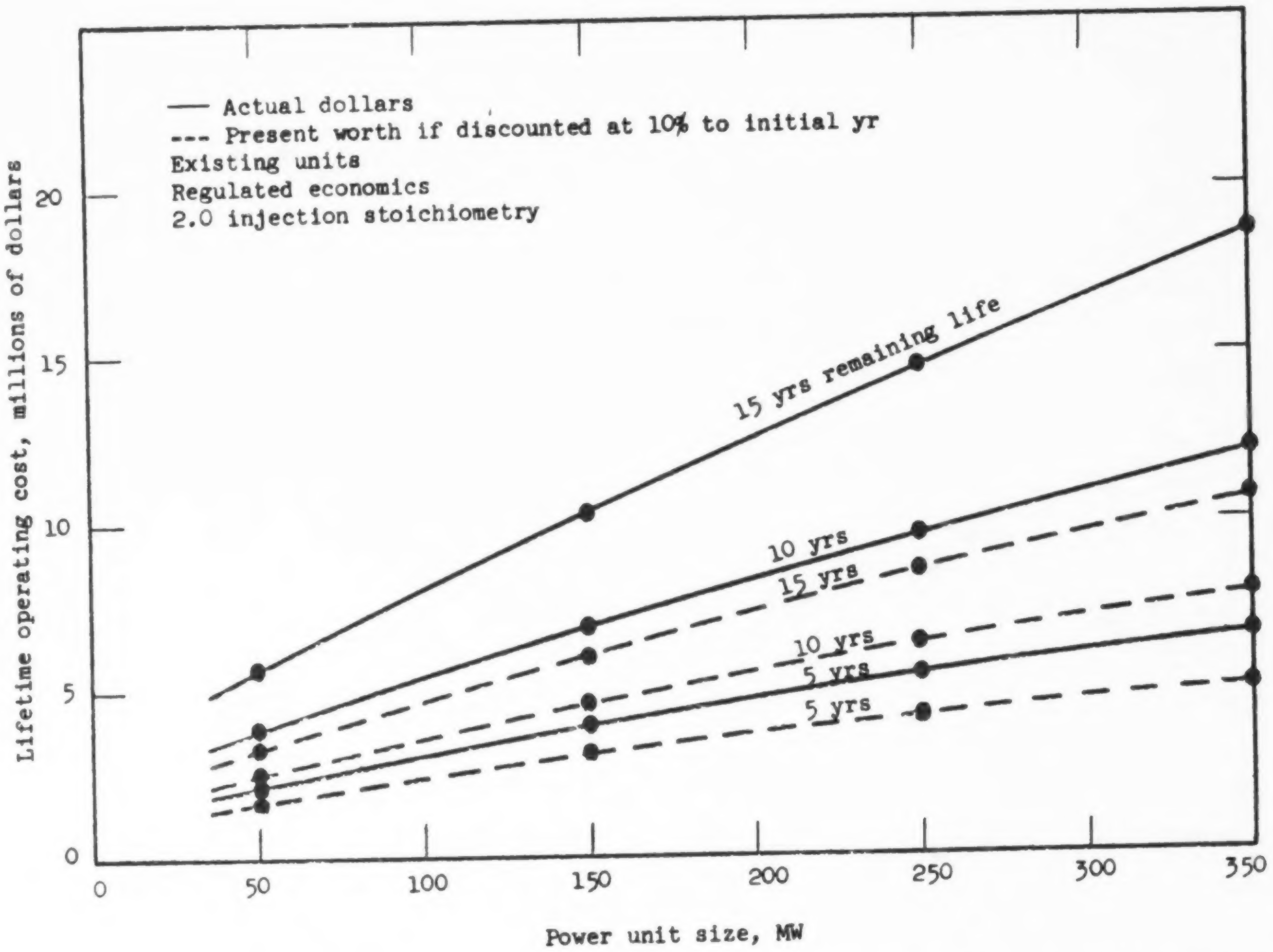

Figure 45. Effect of Power Unit Size and Years Remaining Life on Lifetime Increase in Cost of Power Using Dry Limestone Injection: 3.0% S Coal

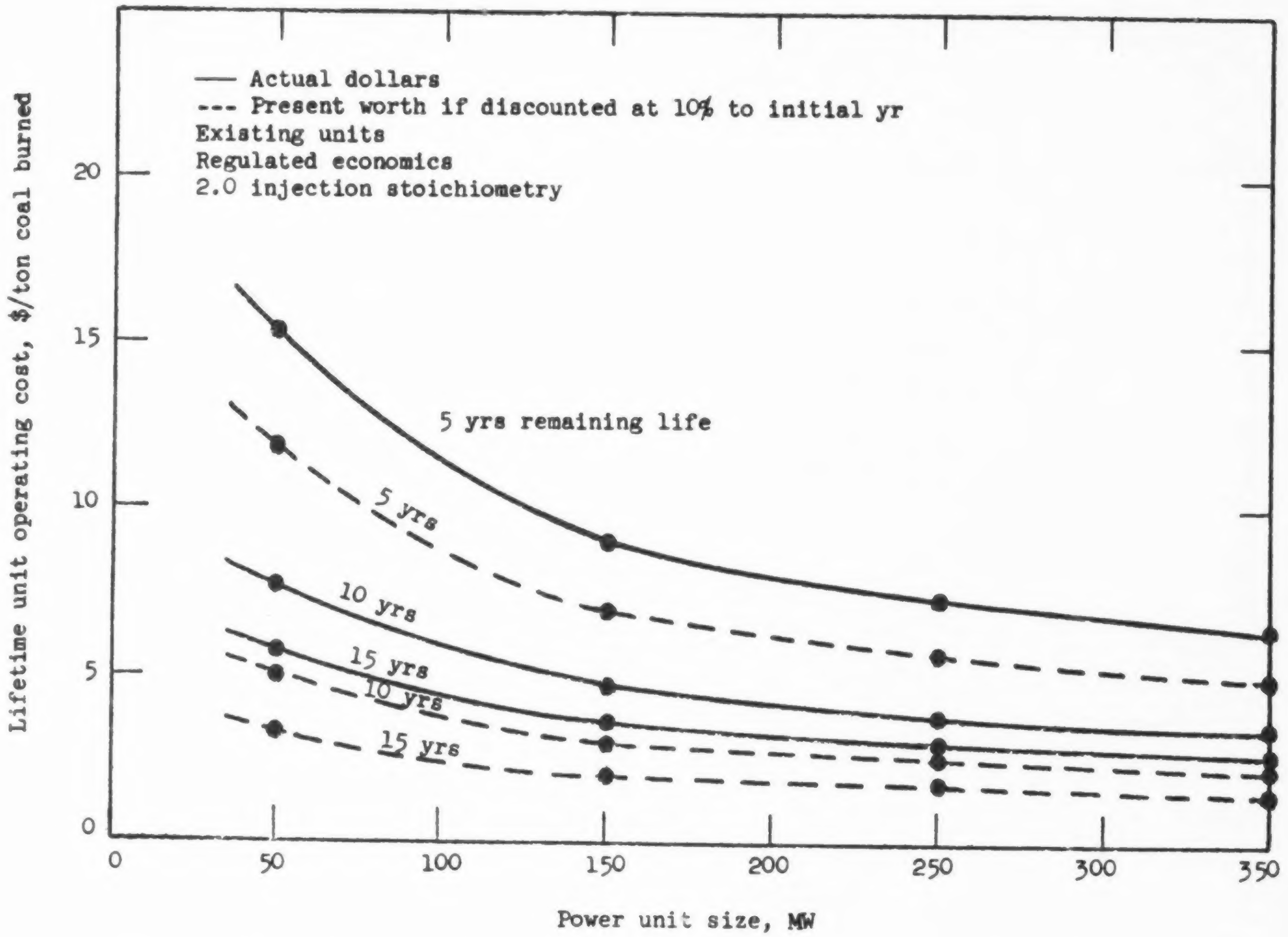

Figure 46. Effect of Power Unit Size and Years Remaining Life on Dry Limestone Process Operating Cost Per Ton of Coal Burned Over Life of Plant: 3.0% S Coal

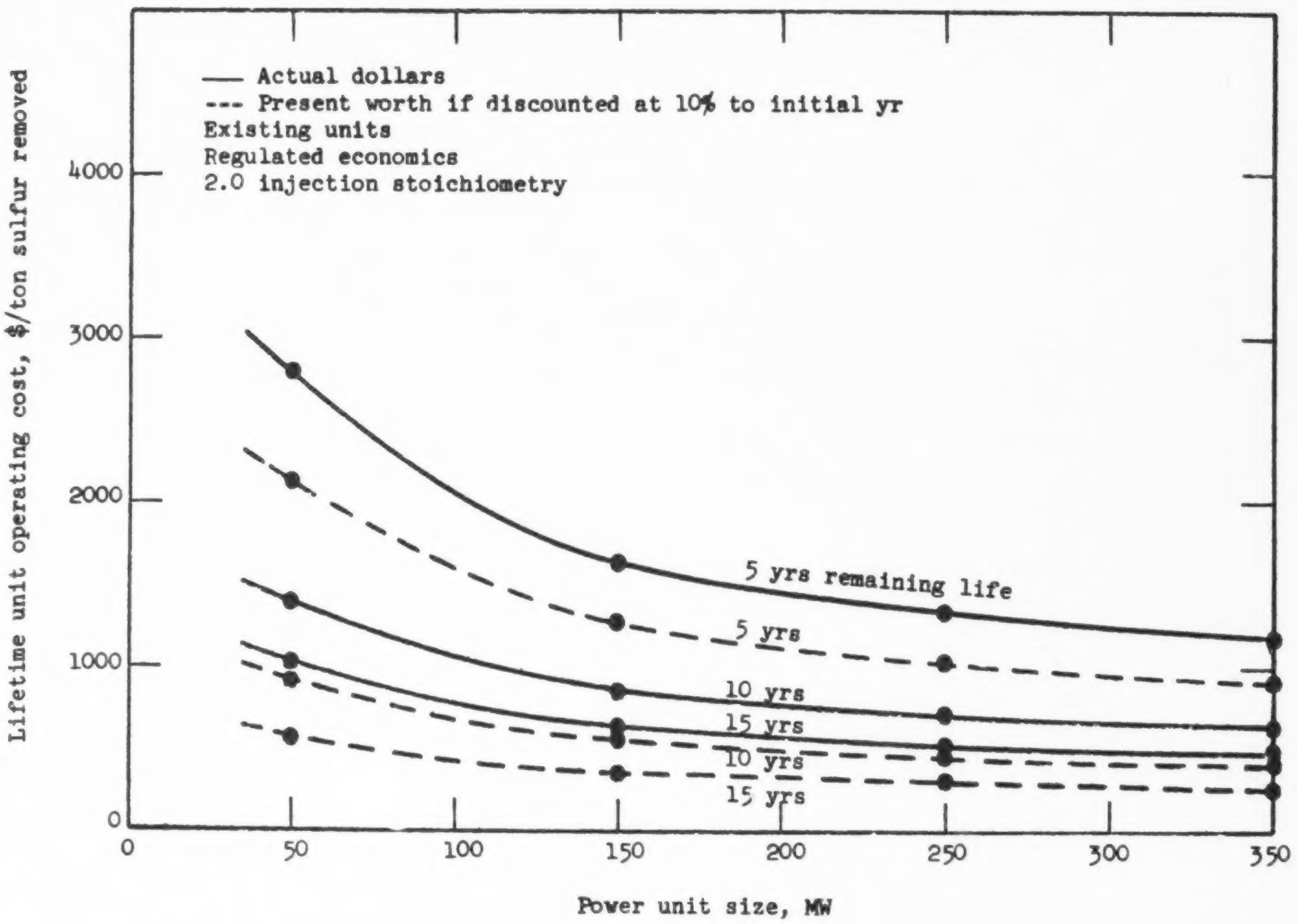

Figure 47. Effect of Power Unit Size and Years Remaining Life on Dry Limestone Process Operating Cost Per Ton of Sulfur Removed Over Life of Plant: 3.0% S Coal

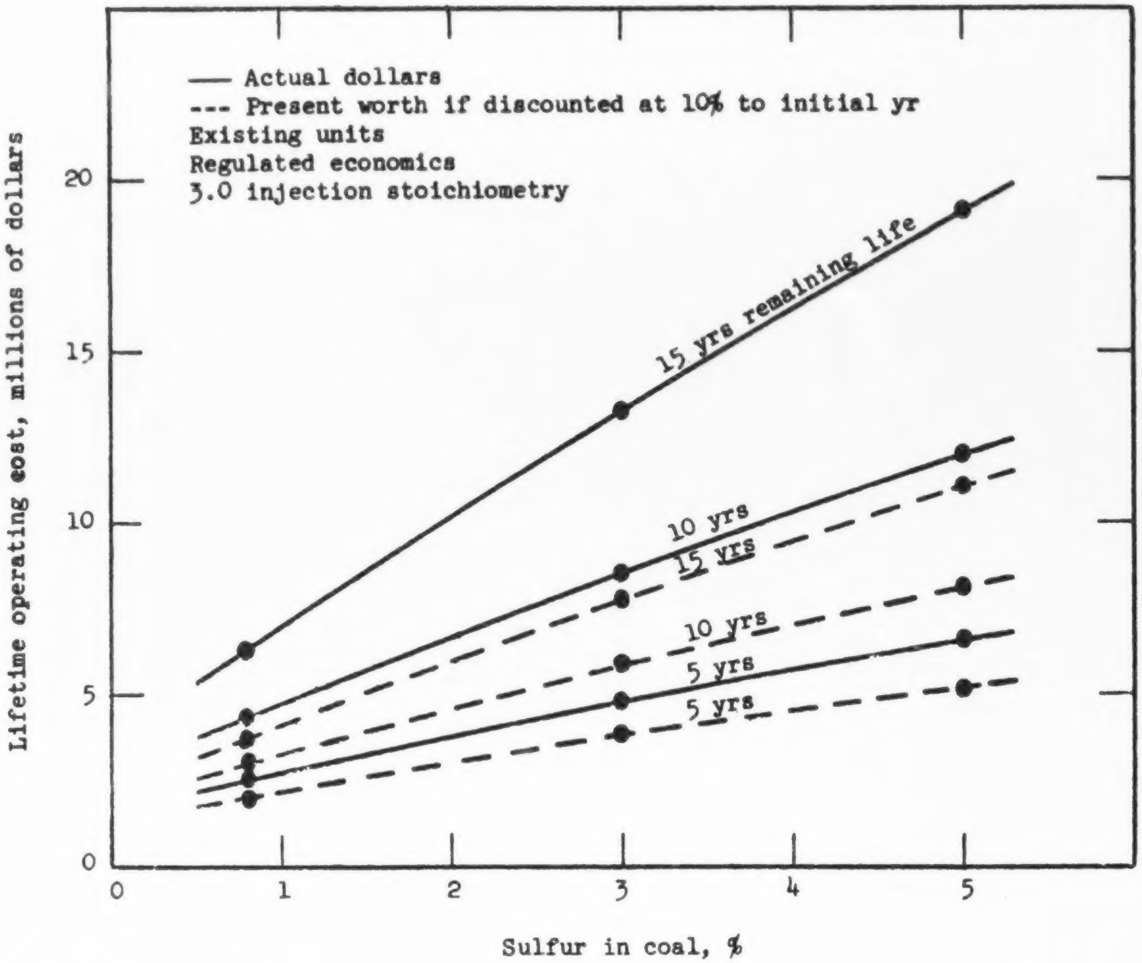

Figure 48. Effect of Sulfur Content of Coal and Years Remaining Life on Lifetime Increase in Cost of Power Using Dry Limestone Injection: 150 MW Units

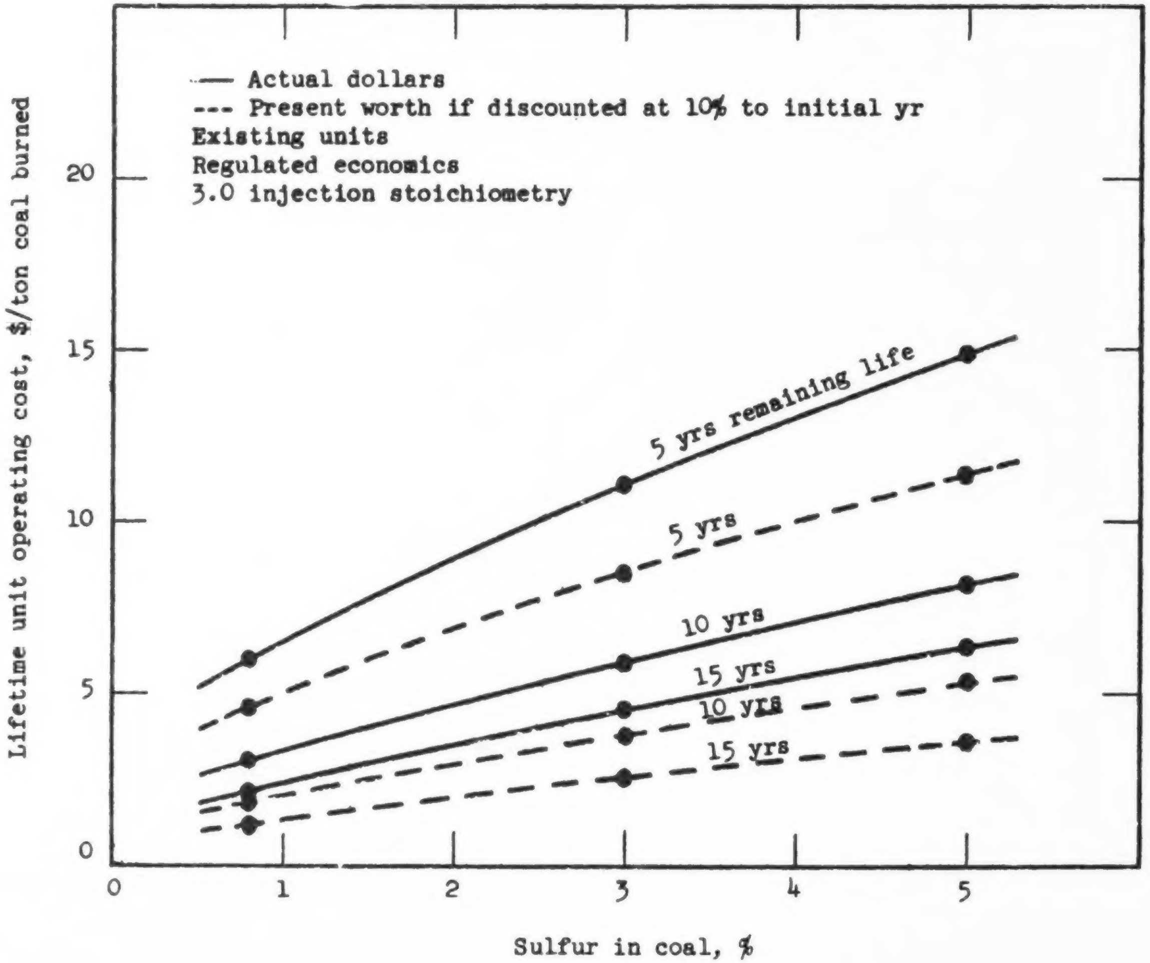

Figure 49. Effect of Sulfur Content of Coal and Years Remaining Life on Dry Limestone Process Operating Cost Per Ton of Coal Burned Over Life of Plant: 150 MW Units

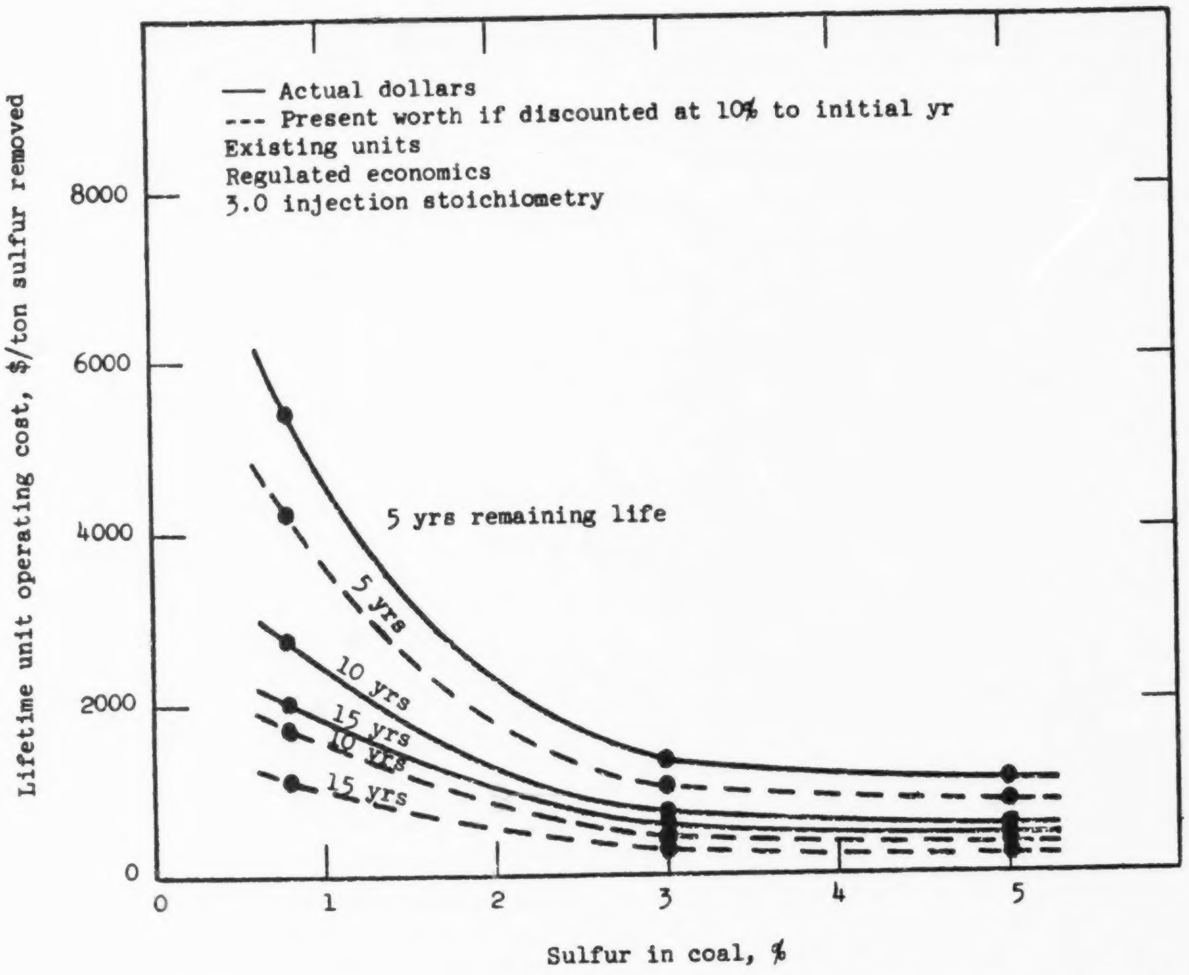

Figure 50. Effect of Sulfur Content of Coal and Years Remaining Life on Dry Limestone Process Operating Cost Per Ton of Sulfur Removed Over Life of Plant: 150 MW Units

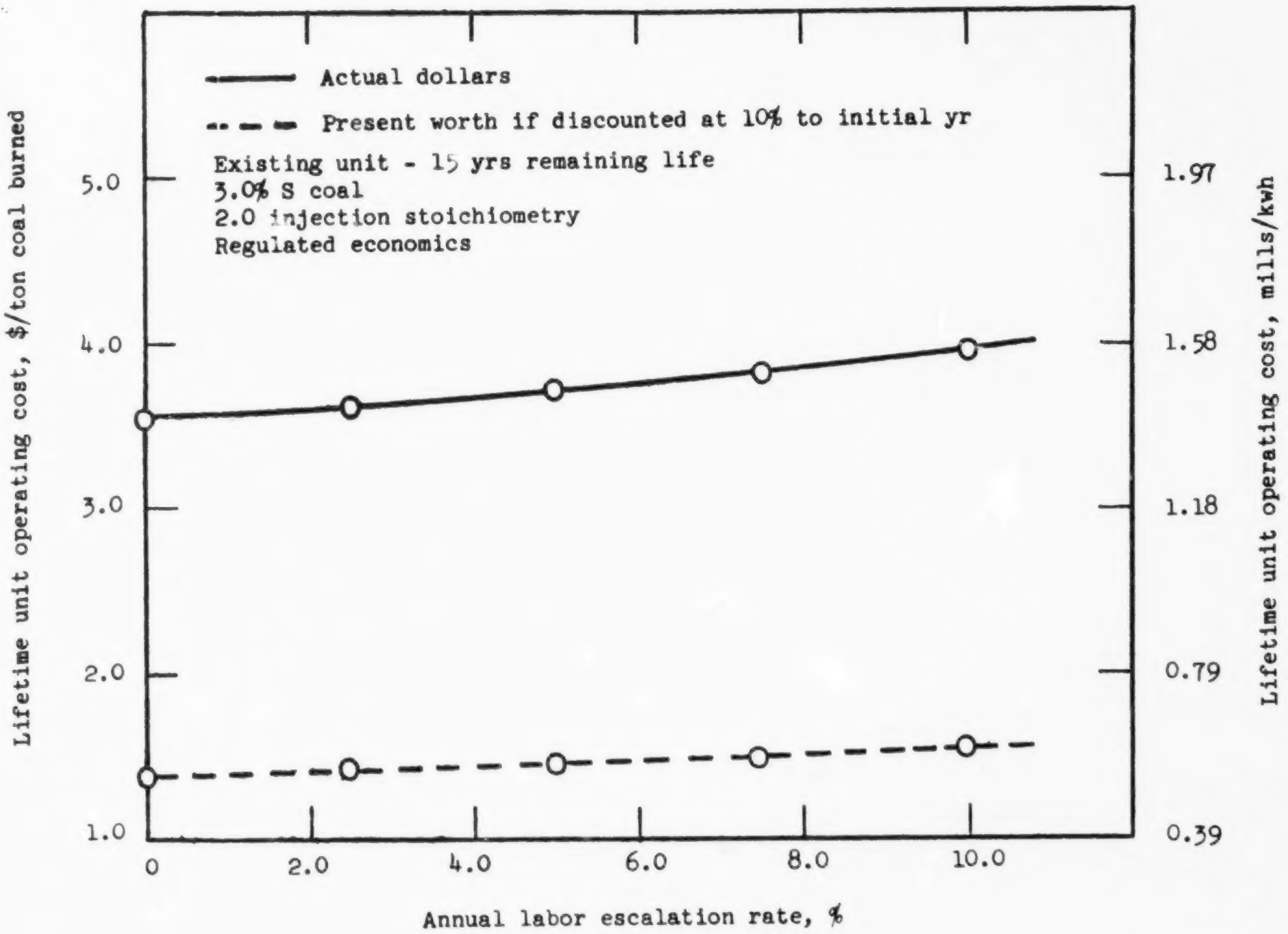

Figure 51. Effect of Escalating Labor Rate on Dry Limestone Process Operating Cost Per Ton of Coal Burned and Per Kilowatt-hour of Electricity Produced Over Life of Plant: 150 MW Unit

III. References and Abstracts

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2. Brown, C. B., Jr. (Koppers Company, Inc.). Private communication to William H. Kennedy, May 23, 1972, giving up-to-date price data on rotary dryers and grinding mills for processing limestone prior to injection into a boiler.
3. Brown, R. F. (Cottrell Environmental Systems, Inc.). Private communications to Robert L. Torstrick, June 30 and July 6, 1972, giving incremental electrostatic precipitator investment and electricity requirements applicable for installing and operating precipitators on power units utilizing the dry limestone injection process.
4. "Economic Indicators." *Chemical Engineering* 79(21), September 18, 1972.

   C. E. Plant Cost Index data was used for obtaining a projected 1972 annual index. This projected index was compared with the annual index for 1969, and used in updating the Shawnee 1969 investment costs.
5. Federal Power Commission. *Hydroelectric Power Evaluation. FPC P-35* (1968) and *Supplement No. 1, FPC P-38* (1969). Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

   This publication is a guide for the evaluation of the hydroelectric power aspects of water resource developments. Included is information concerning investment and operating costs of hydroelectric and thermal-electric power plants and transmission facilities, methods for economic analysis of projects, and methods for presenting the annual costs associated with power generation and transmission under regulated economics.
6. Guthrie, K. M. "Capital Cost Estimating." *Chemical Engineering* 76(6), March 24, 1969.

   Data and techniques for preliminary capital cost estimating are presented along with a compilation of costs for a large variety of plant equipment. A "module" technique for making fast, accurate, and consistent estimates is introduced. Especially useful for this study are the equipment scale factors given in the data.
7. "Industry Statistics." *Oil and Gas Journal* 70(37), September 11, 1972.

   Published data giving refined-products prices was used to obtain the price for distillate kerosine (No. 2 fuel oil) for use in projecting 1972 operating costs for the dry limestone injection process.
8. The M. W. Kellogg Company. *Availability of Limestones and Dolomites. Task No. 1 Final Report*, MWKLG-RED-72-1265, Submitted to Environmental Protection Agency, Contract No. CPA 706-8, February 1, 1972.

   Several processes which remove sulfur oxides from power plant stack gas are based on the use of limestone or dolomite as the absorbent. The objective of this study was to determine the availability and costs of limestone and similar materials throughout the contiguous United States to supplement experimental work.

   Materials covered in this study include limestone, dolomite, chalk, marble, marl, and shell. Information is presented on location of deposits, production rates, f.o.b. quarry costs, transportation methods and costs, expected cost increases, uses, chemical composition, and physical properties.

9. Perry, John H., Chilton, Cecil H., and Kirkpatrick, Sidney D. ***Chemical Engineers' Handbook.*** Fourth Edition, McGraw-Hill Book Co., New York, 1963.

   "Six-tenths factor" method for scaling equipment costs as a function of capacity is presented along with a set of typical exponents for use with various types of equipment.

10. Peters, Max S. and Timmerhaus, Klaus D. ***Plant Design and Economics for Chemical Engineers.*** Second Edition, McGraw-Hill Book Co., New York, 1968.

    Economic and design principles, as applied in chemical engineering processes and operations are discussed. The first part of the text presents an overall analysis of the major factors involved in process design, with particular emphasis on economics in the process industries and in design work. The various costs involved in industrial processes, capital investments and investment returns, cost estimation, cost accounting, optimum economic design methods, and other subjects dealing with economics are covered both qualitatively and quantitatively. The remainder of the book deals with methods and important factors in the design of plants and equipment. Generalized subjects, such as waste disposal, structural design, and equipment fabrication, are included along with design methods for different types of process equipment. Basic cost data and cost correlations are also presented for use in making cost estimates.

11. Purcell, Robert W. (The Taulman Company). Private communication to W. H. Kennedy, June 28, 1972, describing design of sluice systems for disposal of waste solids.

12. Tennessee Valley Authority. ***Sulfur Oxide Removal from Power Plant Stack Gas: Sorption by Limestone or Lime—Dry Process*** (1968). ***Report No. PB 178-972,*** Clearinghouse for Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia 22151.

    Injection of dry limestone or lime into the boiler is considered the simplest and least costly process for removing SO_2 from power plant stack gases. Product is calcium sulfate which is discarded. The process can be operated intermittently. A detailed economic evaluation is presented.

13. Tennessee Valley Authority. "Wage Schedules." Office Service Branch, Administrative Releases (Memorandum No. 1321), August 1, 1972.

    TVA wage schedules effective during 1972 are given for chemical and power plant operators and laborers.

Table A-1 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
1.55 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	6,300
Limestone storage and feed system including hoppers, unloaders, and conveyors	14,400
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	38,400
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	58,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	57,600
Equipment foundations for all areas	16,300
Instrumentation for all areas including panel and shed	27,100
Piping for all areas	35,100
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	33,300
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	42,000
Incremental electrostatic precipitator system[c]	89,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	518,300
Engineering design and overheads	46,600
Construction expense	72,600
Contractors fees	46,600
Contingency	67,400
Total fixed capital investment	751,500

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

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Table A-2 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
2.07 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	7,200
Limestone storage and feed system including hoppers, unloaders, and conveyors	18,200
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	44,300
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	71,200
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	64,700
Equipment foundations for all areas	19,400
Instrumentation for all areas including panel and shed	29,200
Piping for all areas	40,600
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	38,000
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	48,500
Incremental electrostatic precipitator system[c]	94,200
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	575,500
Engineering design and overheads	51,800
Construction expense	80,600
Contractors fees	51,800
Contingency	74,800
Total fixed capital investment	834,500

Basis:

[a] Midwest location – 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-3 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
5.0 Moles CaO Injected per Mole S in Fuel;
2.59 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	8,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	21,800
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	49,700
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	82,000
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	70,800
Equipment foundations for all areas	22,200
Instrumentation for all areas including panel and shed	30,800
Piping for all areas	45,500
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	41,900
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	54,300
Incremental electrostatic precipitator system[c]	99,300
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	626,400
Engineering design and overheads	56,400
Construction expense	87,700
Contractors fees	56,400
Contingency	81,400
Total fixed capital investment	908,300

Basis:

[a] Midwest location--1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-4 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
6.0 Moles CaO Injected per Mole S in Fuel;
3.11 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	8,900
Limestone storage and feed system including hoppers, unloaders, and conveyors	25,100
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	54,400
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	92,500
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	76,200
Equipment foundations for all areas	24,700
Instrumentation for all areas including panel and shed	32,200
Piping for all areas	49,800
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	45,500
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	59,500
Incremental electrostatic precipitator system[c]	103,600
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	672,400
Engineering design and overheads	60,500
Construction expense	94,100
Contractors fees	60,500
Contingency	87,400
Total fixed capital investment	974,900

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-5 Summary of Estimated Fixed Investment[a]–Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
7.0 Moles CaO Injected per Mole S in Fuel;
3.63 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	9,600
Limestone storage and feed system including hoppers, unloaders, and conveyors	28,400
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	58,800
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	102,100
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	81,000
Equipment foundations for all areas	27,200
Instrumentation for all areas including panel and shed	33,500
Piping for all areas	53,800
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	48,900
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	64,300
Incremental electrostatic precipitator system[c]	107,200
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	714,800
Engineering design and overheads	64,300
Construction expense	100,000
Contractors fees	64,300
Contingency	92,900
Total fixed capital investment	1,036,300

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-6 Summary of Estimated Fixed Investment[a]–Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
4.64 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	10,800
Limestone storage and feed system including hoppers, unloaders, and conveyors	34,600
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	66,300
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	119,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	89,200
Equipment foundations for all areas	31,400
Instrumentation for all areas including panel and shed	35,600
Piping for all areas	60,700
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	54,500
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	72,600
Incremental electrostatic precipitator system[c]	226,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	901,500
Engineering design and overheads	72,100
Construction expense	117,200
Contractors fees	72,100
Contingency	117,200
Total fixed capital investment	1,280,100

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-7 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
6.20 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	12,500
Limestone storage and feed system including hoppers, unloaders, and conveyors	43,600
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	76,600
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	144,500
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	100,200
Equipment foundations for all areas	37,400
Instrumentation for all areas including panel and shed	38,300
Piping for all areas	70,200
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	62,000
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	83,800
Incremental electrostatic precipitator system[c]	239,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,008,100
Engineering design and overheads	80,600
Construction expense	131,100
Contractors fees	80,600
Contingency	131,100
Total fixed capital investment	1,431,500

Basis:

[a] Midwest location – 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-8 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
5.0 Moles CaO Injected per Mole S in Fuel;
7.76 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	14,000
Limestone storage and feed system including hoppers, unloaders, and conveyors	52,100
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	85,700
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	167,100
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	109,600
Equipment foundations for all areas	42,800
Instrumentation for all areas including panel and shed	40,500
Piping for all areas	78,500
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	68,700
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	93,800
Incremental electrostatic precipitator system[c]	252,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,104,800
Engineering design and overheads	88,400
Construction expense	143,600
Contractors fees	88,400
Contingency	143,600
Total fixed capital investment	1,568,800

Basis:

[a] Midwest location–1972 costs.

[b] 0″ x 1½″ limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-9 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
6.0 Moles CaO Injected per Mole S in Fuel;
9.33 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	15,300
Limestone storage and feed system including hoppers, unloaders, and conveyors	60,400
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	94,000
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	188,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	118,000
Equipment foundations for all areas	47,800
Instrumentation for all areas including panel and shed	42,500
Piping for all areas	86,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	74,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	102,800
Incremental electrostatic precipitator system[c]	263,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,193,200
Engineering design and overheads	95,500
Construction expense	155,100
Contractors fees	95,500
Contingency	155,100
Total fixed capital investment	1,694,400

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-10 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
7.0 Moles CaO Injected per Mole S in Fuel;
10.90 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	16,600
Limestone storage and feed system including hoppers, unloaders, and conveyors	68,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	101,600
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	208,600
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	125,500
Equipment foundations for all areas	52,400
Instrumentation for all areas including panel and shed	44,100
Piping for all areas	93,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	80,000
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	111,100
Incremental electrostatic precipitator system[c]	272,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,273,200
Engineering design and overheads	101,900
Construction expense	165,500
Contractors fees	101,900
Contingency	165,500
Total fixed capital investment	1,808,000

Basis:

[a] Midwest location--1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-11 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
7.73 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	14,000
Limestone storage and feed system including hoppers, unloaders, and conveyors	52,000
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	85,600
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	167,100
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	109,500
Equipment foundations for all areas	42,700
Instrumentation for all areas including panel and shed	40,500
Piping for all areas	78,300
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	68,500
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	93,600
Incremental electrostatic precipitator system[c]	350,300
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,202,100
Engineering design and overheads	96,200
Construction expense	144,300
Contractors fees	96,200
Contingency	156,300
Total fixed capital investment	1,695,100

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-12 Summary of Estimated Fixed Investment[a]–Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
10.33 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	16,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	65,600
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	99,000
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	179,500
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	123,000
Equipment foundations for all areas	50,800
Instrumentation for all areas including panel and shed	43,500
Piping for all areas	90,600
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	78,100
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	108,200
Incremental electrostatic precipitator system[c]	370,500
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,324,900
Engineering design and overheads	106,000
Construction expense	159,000
Contractors fees	106,000
Contingency	172,200
Total fixed capital investment	1,868,100

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-13 Summary of Estimated Fixed Investment[a]-- Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
5.0 Moles CaO Injected per Mole S in Fuel;
12.93 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	18,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	78,600
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	110,800
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	233,400
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	134,600
Equipment foundations for all areas	58,200
Instrumentation for all areas including panel and shed	46,100
Piping for all areas	101,400
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	86,500
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	121,200
Incremental electrostatic precipitator system[c]	390,600
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,479,500
Engineering design and overheads	118,400
Construction expense	177,500
Contractors fees	118,400
Contingency	192,300
Total fixed capital investment	2,086,100

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

TableA-14 Summary of Estimated Fixed Investment[a]–Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
6.0 Moles CaO Injected per Mole S in Fuel;
15.55 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	19,800
Limestone storage and feed system including hoppers, unloaders, and conveyors	90,900
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	121,400
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	262,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	144,700
Equipment foundations for all areas	64,900
Instrumentation for all areas including panel and shed	48,200
Piping for all areas	111,100
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	93,900
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	132,800
Incremental electrostatic precipitator system[c]	407,700
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,598,200
Engineering design and overheads	127,900
Construction expense	191,800
Contractors fees	127,900
Contingency	207,800
Total fixed capital investment	2,253,600

Basis:

[a] Midwest location – 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-15 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
7.0 Moles CaO Injected per Mole S in Fuel;
18.17 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	21,400
Limestone storage and feed system including hoppers, unloaders, and conveyors	103,000
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	131,100
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	290,900
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	154,100
Equipment foundations for all areas	71,200
Instrumentation for all areas including panel and shed	50,100
Piping for all areas	120,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	100,700
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	143,500
Incremental electrostatic precipitator system[c]	421,600
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,707,600
Engineering design and overheads	136,600
Construction expense	204,900
Contractors fees	136,600
Contingency	222,000
Total fixed capital investment	2,407,700

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-16 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
10.83 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	16,500
Limestone storage and feed system including hoppers, unloaders, and conveyors	68,100
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	101,300
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	208,000
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	125,300
Equipment foundations for all areas	52,200
Instrumentation for all areas including panel and shed	44,100
Piping for all areas	92,700
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	79,800
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	110,800
Incremental electrostatic precipitator system[c]	463,300
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,462,100
Engineering design and overheads	102,300
Construction expense	175,500
Contractors fees	102,300
Contingency	190,100
Total fixed capital investment	2,032,300

Basis:

[a] Midwest location – 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-17 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
14.47 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	19,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	85,800
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	117,100
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	251,000
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	140,700
Equipment foundations for all areas	62,200
Instrumentation for all areas including panel and shed	47,300
Piping for all areas	107,200
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	90,900
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	128,100
Incremental electrostatic precipitator system[c]	490,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,639,400
Engineering design and overheads	114,800
Construction expense	196,700
Contractors fees	114,800
Contingency	213,100
Total fixed capital investment	2,278,800

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-18 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
5.0 Moles CaO Injected per Mole S in Fuel;
18.11 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	21,400
Limestone storage and feed system including hoppers, unloaders, and conveyors	102,700
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	131,000
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	290,300
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	153,800
Equipment foundations for all areas	71,100
Instrumentation for all areas including panel and shed	50,100
Piping for all areas	119,900
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	100,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	143,300
Incremental electrostatic precipitator system[c]	516,600
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,800,800
Engineering design and overheads	126,100
Construction expense	216,100
Contractors fees	126,100
Contingency	234,100
Total fixed capital investment	2,503,200

Basis:

[a] Midwest location – 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-19 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
6.0 Moles CaO Injected per Mole S in Fuel;
21.77 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	23,400
Limestone storage and feed system including hoppers, unloaders, and conveyors	119,000
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	143,700
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	327,200
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	165,700
Equipment foundations for all areas	79,400
Instrumentation for all areas including panel and shed	52,500
Piping for all areas	131,500
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	109,200
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	157,100
Incremental electrostatic precipitator system[c]	539,200
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,947,900
Engineering design and overheads	136,400
Construction expense	233,700
Contractors fees	136,400
Contingency	253,300
Total fixed capital investment	2,707,700

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

TableA-20 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 0.8% S in Fuel;
7.0 Moles CaO Injected per Mole S in Fuel;
25.43 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	25,300
Limestone storage and feed system including hoppers, unloaders, and conveyors	134,700
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	155,200
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	361,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	176,200
Equipment foundations for all areas	87,200
Instrumentation for all areas including panel and shed	54,500
Piping for all areas	142,100
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	117,100
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	169,800
Incremental electrostatic precipitator system[c]	557,600
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	2,081,500
Engineering design and overheads	145,700
Construction expense	249,800
Contractors fees	145,700
Contingency	270,600
Total fixed capital investment	2,893,300

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

TableA-21 Summary of Estimated Fixed Investment[a]–Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
1.93 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	7,000
Limestone storage and feed system including hoppers, unloaders, and conveyors	17,200
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	42,800
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	67,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	62,900
Equipment foundations for all areas	18,600
Instrumentation for all areas including panel and shed	28,700
Piping for all areas	39,200
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	36,800
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	46,800
Incremental electrostatic precipitator system[c]	95,700
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	563,500
Engineering design and overheads	50,700
Construction expense	78,900
Contractors fees	50,700
Contingency	73,300
Total fixed capital investment	817,100

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-22 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
3.89 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	9,900
Limestone storage and feed system including hoppers, unloaders, and conveyors	30,000
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	60,800
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	107,100
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	83,200
Equipment foundations for all areas	28,300
Instrumentation for all areas including panel and shed	34,100
Piping for all areas	55,700
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	50,400
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	66,500
Incremental electrostatic precipitator system[c]	112,300
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	738,300
Engineering design and overheads	66,400
Construction expense	103,400
Contractors fees	66,400
Contingency	96,000
Total fixed capital investment	1,070,500

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-23 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
5.87 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	12,200
Limestone storage and feed system including hoppers, unloaders, and conveyors	41,800
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	74,600
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	139,600
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	98,100
Equipment foundations for all areas	36,200
Instrumentation for all areas including panel and shed	37,800
Piping for all areas	68,300
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	60,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	81,600
Incremental electrostatic precipitator system[c]	126,100
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	876,900
Engineering design and overheads	78,900
Construction expense	122,800
Contractors fees	78,900
Contingency	114,000
Total fixed capital investment	1,271,500

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-24 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
7.86 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	14,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	52,700
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	86,300
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	168,700
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	110,100
Equipment foundations for all areas	43,100
Instrumentation for all areas including panel and shed	40,700
Piping for all areas	79,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	69,100
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	94,400
Incremental electrostatic precipitator system[c]	136,300
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	994,500
Engineering design and overheads	89,500
Construction expense	139,200
Contractors fees	89,500
Contingency	129,300
Total fixed capital investment	1,442,000

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-25 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
5.80 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	12,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	41,200
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	74,200
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	138,400
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	97,500
Equipment foundations for all areas	35,900
Instrumentation for all areas including panel and shed	37,700
Piping for all areas	67,900
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	60,200
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	81,100
Incremental electrostatic precipitator system[c]	243,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	989,200
Engineering design and overheads	79,100
Construction expense	128,600
Contractors fees	79,100
Contingency	128,600
Total fixed capital investment	1,404,600

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-26 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
11.67 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	17,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	72,200
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	105,100
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	218,200
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	129,000
Equipment foundations for all areas	54,600
Instrumentation for all areas including panel and shed	44,900
Piping for all areas	96,200
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	82,500
Revisions aand additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	115,000
Incremental electrostatic precipitator system[c]	285,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,319,800
Engineering design and overheads	105,600
Construction expense	171,600
Contractors fees	105,600
Contingency	171,600
Total fixed capital investment	1,874,200

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-27 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
17.60 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	21,000
Limestone storage and feed system including hoppers, unloaders, and conveyors	100,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	129,100
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	284,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	152,100
Equipment foundations for all areas	69,900
Instrumentation for all areas including panel and shed	49,800
Piping for all areas	118,200
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	99,200
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	141,200
Incremental electrostatic precipitator system[c]	320,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,585,600
Engineering design and overheads	126,800
Construction expense	206,100
Contractors fees	126,800
Contingency	206,100
Total fixed capital investment	2,251,400

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-28 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
23.59 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	24,400
Limestone storage and feed system including hoppers, unloaders, and conveyors	126,900
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	149,400
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	344,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	171,000
Equipment foundations for all areas	83,300
Instrumentation for all areas including panel and shed	53,500
Piping for all areas	136,800
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	113,200
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	163,500
Incremental electrostatic precipitator system[c]	346,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,812,800
Engineering design and overheads	145,000
Construction expense	235,700
Contractors fees	145,000
Contingency	235,700
Total fixed capital investment	2,574,200

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-29 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
9.67 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	15,600
Limestone storage and feed system including hoppers, unloaders, and conveyors	62,200
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	95,800
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	193,100
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	119,700
Equipment foundations for all areas	48,800
Instrumentation for all areas including panel and shed	42,800
Piping for all areas	87,700
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	75,800
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	104,800
Incremental electrostatic precipitator system[c]	376,700
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,323,000
Engineering design and overheads	105,900
Construction expense	158,800
Contractors fees	105,900
Contingency	172,000
Total fixed capital investment	1,865,600

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-30 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
19.45 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and ydrains	22,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	108,700
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	135,700
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	303,900
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	158,300
Equipment foundations for all areas	74,200
Instrumentation for all areas including panel and shed	51,000
Piping for all areas	124,200
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	103,900
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	148,400
Incremental electrostatic precipitator system[c]	441,800
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,772,200
Engineering design and overheads	141,800
Construction expense	212,700
Contractors fees	141,800
Contingency	230,400
Total fixed capital investment	2,498,900

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

TableA-31 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
29.33 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	27,200
Limestone storage and feed system including hoppers, unloaders, and conveyors	151,000
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	166,600
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	397,100
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	186,600
Equipment foundations for all areas	95,000
Instrumentation for all areas including panel and shed	56,500
Piping for all areas	152,500
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	124,900
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	182,300
Incremental electrostatic precipitator system[c]	496,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	2,135,700
Engineering design and overheads	170,900
Construction expense	256,300
Contractors fees	170,900
Contingency	277,600
Total fixed capital investment	3,011,400

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-32 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
39.32 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	31,500
Limestone storage and feed system including hoppers, unloaders, and conveyors	190,800
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	192,900
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	480,400
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	209,700
Equipment foundations for all areas	113,200
Instrumentation for all areas including panel and shed	60,800
Piping for all areas	176,600
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	142,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	211,000
Incremental electrostatic precipitator system[c]	536,300
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	135,000
Subtotal ddirect investment	2,480,800
Engineering design and overheads	198,500
Construction expense	297,700
Contractors fees	198,500
Contingency	322,500
Total fixed capital investment	3,498,000

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-33 Summary of Estimated Fixed Investment[a]–Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
13.53 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	18,500
Limestone storage and feed system including hoppers, unloaders, and conveyors	81,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	113,200
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	240,200
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	137,000
Equipment foundations for all areas	59,700
Instrumentation for all areas including panel and shed	46,600
Piping for all areas	103,700
Electrical power supply including 4160 and 480 volt boards and conduit, trays, grounding, and telephone	88,200
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	123,900
Incremental electrostatic precipitator system[c]	498,200
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,610,500
Engineering design and overheads	112,700
Construction expense	193,300
Contractors fees	112,700
Contingency	209,400
Total fixed capital investment	2,238,600

Basis:

[a] Midwest location–1972 costs.

[b] 0″ x 1½″ limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-34 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
27.23 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	26,200
Limestone storage and feed system including hoppers, unloaders, and conveyors	142,200
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	160,600
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	378,200
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	181,200
Equipment foundations for all areas	90,800
Instrumentation for all areas including panel and shed	55,500
Piping for all areas	147,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	120,800
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	175,700
Incremental electrostatic precipitator system[c]	584,300
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	2,162,500
Engineering design and overheads	151,400
Construction expense	259,500
Contractors fees	151,400
Contingency	281,100
Total fixed capital investment	3,005,900

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-35 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
41.07 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	32,100
Limestone storage and feed system including hoppers, unloaders, and conveyors	197,700
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	197,200
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	494,300
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	213,500
Equipment foundations for all areas	116,200
Instrumentation for all areas including panel and shed	61,500
Piping for all areas	180,500
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	145,400
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	215,700
Incremental electrostatic precipitator system[c]	656,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	135,000
Subtotal direct investment	2,645,100
Engineering design and overheads	185,200
Construction expense	317,400
Contractors fees	185,200
Contingency	343,900
Total fixed capital investment	3,676,800

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-36 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 3.0% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
55.04 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	37,200
Limestone storage and feed system including hoppers, unloaders, and conveyors	249,800
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	228,300
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	597,700
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	239,900
Equipment foundations for all areas	138,500
Instrumentation for all areas including panel and shed	66,100
Piping for all areas	209,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	165,800
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	249,700
Incremental electrostatic precipitator system[c]	709,300
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	175,000
Subtotal direct investment	3,066,300
Engineering design and overheads	214,600
Construction expense	368,000
Contractors fees	214,600
Contingency	398,600
Total fixed capital investment	4,262,100

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-37 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
3.23 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	9,000
Limestone storage and feed system including hoppers, unloaders, and conveyors	25,900
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	55,300
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	94,700
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	77,300
Equipment foundations for all areas	25,400
Instrumentation for all areas including panel and shed	32,600
Piping for all areas	50,600
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	46,400
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	60,500
Incremental electrostatic precipitator system[c]	108,700
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	686,400
Engineering design and overheads	61,800
Construction expense	96,100
Contractors fees	61,800
Contingency	89,200
Total fixed capital investment	995,300

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-38 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
6.53 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	12,800
Limestone storage and feed system including hoppers, unloaders, and conveyors	45,400
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	78,700
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	149,800
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	102,300
Equipment foundations for all areas	38,600
Instrumentation for all areas including panel and shed	38,800
Piping for all areas	72,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	63,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	86,100
Incremental electrostatic precipitator system[c]	131,200
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	919,300
Engineering design and overheads	82,700
Construction expense	128,700
Contractors fees	82,700
Contingency	119,500
Total fixed capital investment	1,332,900

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-39 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
9.89 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	15,800
Limestone storage and feed system including hoppers, unloaders, and conveyors	63,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	96,900
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	195,900
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	120,900
Equipment foundations for all areas	49,500
Instrumentation for all areas including panel and shed	43,100
Piping for all areas	88,700
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	76,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	106,000
Incremental electrostatic precipitator system[c]	148,500
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,105,200
Engineering design and overheads	99,500
Construction expense	154,700
Contractors fees	99,500
Contingency	143,700
Total fixed capital investment	1,602,600

Basis:

[a] Midwest location – 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-40 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(50-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
13.33 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	18,300
Limestone storage and feed system including hoppers, unloaders, and conveyors	80,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	112,400
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	238,000
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	136,100
Equipment foundations for all areas	59,200
Instrumentation for all areas including panel and shed	46,400
Piping for all areas	102,900
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	87,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	123,000
Incremental electrostatic precipitator system[c]	163,900
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,268,100
Engineering design and overheads	114,100
Construction expense	177,500
Contractors fees	114,100
Contingency	164,900
Total fixed capital investment	1,838,700

Basis:

[a] Midwest location - 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-41 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
9.70 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	15,600
Limestone storage and feed system including hoppers, unloaders, and conveyors	62,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	95,800
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	193,400
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	119,900
Equipment foundations for all areas	48,300
Instrumentation for all areas including panel and shed	42,900
Piping for all areas	87,700
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	75,900
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	104,800
Incremental electrostatic precipitator system[c]	276,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,222,600
Engineering design and overheads	97,800
Construction expense	159,000
Contractors fees	97,800
Contingency	159,000
Total fixed capital investment	1,736,200

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

TableA-42 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
19.59 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	22,200
Limestone storage and feed system including hoppers, unloaders, and conveyors	109,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	136,200
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	305,500
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	158,800
Equipment foundations for all areas	74,500
Instrumentation for all areas including panel and shed	51,100
Piping for all areas	124,700
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	104,200
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	149,000
Incremental electrostatic precipitator system[c]	333,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,668,500
Engineering design and overheads	133,500
Construction expense	217,000
Contractors fees	133,500
Contingency	217,000
Total fixed capital investment	2,369,500

Basis:

[a] Midwest location--1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-43 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
29.66 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	27,300
Limestone storage and feed system including hoppers, unloaders, and conveyors	152,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	167,600
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	399,900
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	187,400
Equipment foundations for all areas	95,600
Instrumentation for all areas including panel and shed	56,700
Piping for all areas	153,400
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	125,500
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	183,300
Incremental electrostatic precipitator system[c]	377,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	135,000
Subtotal direct investment	2,061,000
Engineering design and overheads	164,900
Construction expense	267,900
Contractors fees	164,900
Contingency	267,900
Total fixed capital investment	2,926,600

Basis:

[a] Midwest location – 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-44 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(150-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
39.99 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	31,700
Limestone storage and feed system including hoppers, unloaders, and conveyors	193,400
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	194,600
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	485,600
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	211,300
Equipment foundations for all areas	114,400
Instrumentation for all areas including panel and shed	61,100
Piping for all areas	178,100
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	143,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	212,800
Incremental electrostatic precipitator system[c]	416,000
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	135,000
Subtotal direct investment	2,377,600
Engineering design and overheads	190,200
Construction expense	309,100
Contractors fees	190,200
Contingency	309,100
Total fixed capital investment	3,376,200

Basis:

[a] Midwest location – 1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-45 Summary of Estimated Fixed Investment[a]--Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
16.17 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	20,200
Limestone storage and feed system including hoppers, unloaders, and conveyors	93,800
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	123,700
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	269,600
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	147,100
Equipment foundations for all areas	66,500
Instrumentation for all areas including panel and shed	48,700
Piping for all areas	113,200
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	95,600
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	135,300
Incremental electrostatic precipitator system[c]	427,800
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	1,641,500
Engineering design and overheads	131,300
Construction expense	197,000
Contractors fees	131,300
Contingency	213,400
Total fixed capital investment	2,314,500

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-46 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
32.65 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	28,700
Limestone storage and feed system including hoppers, unloaders, and conveyors	164,400
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	175,900
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	425,600
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	194,800
Equipment foundations for all areas	101,300
Instrumentation for all areas including panel and shed	58,000
Piping for all areas	161,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	131,100
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	192,400
Incremental electrostatic precipitator system[c]	516,200
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	135,000
Subtotal direct investment	2,284,400
Engineering design and overheads	182,800
Construction expense	274,100
Contractors fees	182,800
Contingency	297,000
Total fixed capital investment	3,221,100

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-47 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
49.43 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	35,300
Limestone storage and feed system including hoppers, unloaders, and conveyors	229,200
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	216,300
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	557,400
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	229,900
Equipment foundations for all areas	129,900
Instrumentation for all areas including panel and shed	64,400
Piping for all areas	198,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	158,000
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	236,600
Incremental electrostatic precipitator system[c]	584,400
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	175,000
Subtotal direct investment	2,814,400
Engineering design and overheads	225,200
Construction expense	337,700
Contractors fees	225,200
Contingency	365,900
Total fixed capital investment	3,968,400

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-48 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(250-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
66.65 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	41,000
Limestone storage and feed system including hoppers, unloaders, and conveyors	291,100
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	251,300
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	676,900
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	259,100
Equipment foundations for all areas	155,400
Instrumentation for all areas including panel and shed	69,400
Piping for all areas	230,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	180,700
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	274,900
Incremental electrostatic precipitator system[c]	644,800
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	175,000
Subtotal direct investment	3,249,600
Engineering design and overheads	260,000
Construction expense	390,000
Contractors fees	260,000
Contingency	422,400
Total fixed capital investment	4,582,000

Basis:

[a] Midwest location – 1972 costs.

[b] 0″ x 1½″ limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-49 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
22.63 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	23,900
Limestone storage and feed system including hoppers, unloaders, and conveyors	122,700
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	146,400
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	335,500
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	168,200
Equipment foundations for all areas	81,300
Instrumentation for all areas including panel and shed	52,900
Piping for all areas	134,000
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	111,100
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	160,200
Incremental electrostatic precipitator system[c]	565,800
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	100,000
Subtotal direct investment	2,002,000
Engineering design and overheads	140,100
Construction expense	240,200
Contractors fees	140,100
Contingency	260,300
Total fixed capital investment	2,782,700

Basis:

[a] Midwest location—1972 costs.

[b] 0″ x 1½″ limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-50 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
45.71 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	33,900
Limestone storage and feed system including hoppers, unloaders, and conveyors	215,300
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	208,100
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	529,900
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	222,800
Equipment foundations for all areas	123,900
Instrumentation for all areas including panel and shed	63,200
Piping for all areas	190,500
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	152,500
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	227,600
Incremental electrostatic precipitator system[c]	682,700
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	175,000
Subtotal direct investment	2,825,400
Engineering design and overheads	197,800
Construction expense	339,000
Contractors fees	197,800
Contingency	367,000
Total fixed capital investment	3,927,000

Basis:

[a] Midwest location–1972 costs.

[b] 0″ x 1½″ limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-51 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
69.21 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	41,700
Limestone storage and feed system including hoppers, unloaders, and conveyors	300,000
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	255,900
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	693,600
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	263,000
Equipment foundations for all areas	158,900
Instrumentation for all areas including panel and shed	70,000
Piping for all areas	234,300
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	183,800
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	280,000
Incremental electrostatic precipitator system[c]	772,900
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	175,000
Subtotal direct investment	3,429,100
Engineering design and overheads	240,000
Construction expense	411,500
Contractors fees	240,000
Contingency	445,800
Total fixed capital investment	4,766,400

Basis:

[a] Midwest location—1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-52 Summary of Estimated Fixed Investment[a]—Dry Limestone Injection Process

(350-MW Existing Coal-Fired Power Unit; 5.0% S in Fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
93.31 Tons Dry Limestone per Hour)

	Investment, $
General yard work including landscaping, lighting, grading, raw water piping and drains	48,500
Limestone storage and feed system including hoppers, unloaders, and conveyors	381,000
Limestone drying system including dryer, dust collectors, chutes and ducts, bucket elevator, and dryer shed	297,200
Limestone grinding system[b] including feed bin, ball mill and classifier, storage silo, conveyors and chutes, and dust collectors	842,500
Limestone injection system including transport pump, air compressors, feed tank, conveyors, ducts and chutes, limestone distributor, piping and injectors	296,400
Equipment foundations for all areas	190,100
Instrumentation for all areas including panel and shed	75,500
Piping for all areas	272,100
Electrical power supply including 4160 and 480 volt boards and conduit, trays, groundings, and telephone	210,300
Revisions and additions to powerhouse and boiler including injection ports, metal work, insulation and steam lines	325,100
Incremental electrostatic precipitator system[c]	852,800
Incremental solids disposal system[d] for collecting and sluicing limestone solids to pond	270,000
Subtotal direct investment	4,061,500
Engineering design and overheads	284,300
Construction expense	487,400
Contractors fees	284,300
Contingency	528,000
Total fixed capital investment	5,645,500

Basis:

[a] Midwest location–1972 costs.

[b] 0" x 1½" limestone ground to 80% minus 400 mesh.

[c] Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.

[d] Solids disposed as 15% slurry with no recycle of pond water. Disposal pond located 1 mile from power unit. Cost of solids disposal pond not included.

Table A-53 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
1.55 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	8,200 tons	4.05/ton	33,200
Subtotal raw material			33,200
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	43,500 gal	.11/gal	4,800
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	49,200 kWh	.007/kWh	300
Grinding	437,900 kWh	.007/kWh	3,100
Injection	78,700 kWh	.007/kWh	600
Dust collection (credit)	-58,800 kWh	.007/kWh	(400)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			19,900
Dust collection			2,600
Analyses	50 hr	10.00/hr	500
Subtotal conversion costs			103,400
Subtotal direct costs			136,600
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			132,300
Overhead			
Plant, 20% of conversion costs			20,700
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			159,000
Average annual operating cost for dry limestone injection			295,600
Thermal effect of dry limestone injection on operating cost of power plant			2,800

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.05	298,400

[a] Basis:

Coal burned–97,900 tons/yr; .784 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $751,500
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-54 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
2.07 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	10,900 tons	4.05/ton	44,100
Subtotal raw material			44,100
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	57,800 gal	.11/gal	6,400
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	65,400 kWh	.007/kWh	500
Grinding	582,100 kWh	.007/kWh	4,100
Injection	104,600 kWh	.007/kWh	700
Dust collection (credit)	-57,500 kWh	.007/kWh	(400)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			22,300
Dust collection			2,700
Analyses	50 hr	10.00/hr	500
Subtotal conversion costs			108,800
Subtotal direct costs			152,900
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			146,900
Overhead			
Plant, 20% of conversion costs			21,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			174,700
Average annual operating cost for dry limestone injection			327,600
Thermal effect of dry limestone injection on operating cost of power plant			3,700

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.38	331,300

[a] Basis:

Coal burned–98,100 tons/yr; .785 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
O" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $834,500
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-55 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
5.0 Moles CaO Injected per Mole S in Fuel;
2.59 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	13,700 tons	4.05/ton	55,500
Subtotal raw material			55,500
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	72,600 gal	.11/gal	8,000
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	82,200 kWh	.007/kWh	600
Grinding	731,600 kWh	.007/kWh	5,100
Injection	131,500 kWh	.007/kWh	900
Dust collection	-56,000 kWh	.007/kWh	(400)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			24,300
Dust collection			2,900
Analyses	60 hr	10.00/hr	600
Subtotal conversion costs			114,000
Subtotal direct costs			169,500
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			159,600
Overhead			
Plant, 20% of conversion costs			22,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			188,700
Average annual operating cost for dry limestone injection			358,200
Thermal effect of dry limestone injection on operating cost of power plant			4,600

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.69	362,800

[a] Basis:

Coal burned–98,200 tons/yr; .786 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $908,300
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-56 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
6.0 Moles CaO Injected per Mole S in Fuel;
3.11 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	16,400 tons	4.05/ton	66,400
Subtotal raw material			66,400
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	86,900 gal	.11/gal	9,600
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	98,400 kWh	.007/kWh	700
Grinding	875,800 kWh	.007/kWh	6,100
Injection	157,400 kWh	.007/kWh	1,100
Dust collection (credit)	-55,000 kWh	.007/kWh	(400)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			26,200
Dust collection			3,000
Analyses	70 hr	10.00/hr	700
Subtotal conversion costs			119,000
Subtotal direct costs			185,400
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			171,600
Overhead			
Plant, 20% of conversion costs			23,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			201,400
Average annual operating cost for dry limestone injection			386,800
Thermal effect of dry limestone injection on operating cost of power plant			5,500

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.99	392,300

[a] Basis:

Coal burned–98,400 tons/yr; .787 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $974,900
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-57 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
7.0 Moles CaO Injected per Mole S in Fuel;
3.63 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	19,100 tons	4.05/ton	77,400
Subtotal raw material			77,400
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	101,200 gal	.11/gal	11,100
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	114,600 kWh	.007/kWh	800
Grinding	1,019,900 kWh	.007/kWh	7,100
Injection	183,400 kWh	.007/kWh	1,300
Dust collection (credit)	-53,800 kWh	.007/kWh	(400)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			28,000
Dust collection			3,100
Analyses	80 hr	10.00/hr	800
Subtotal conversion costs			123,800
Subtotal direct costs			201,200
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			182,400
Overhead			
Plant, 20% of conversion costs			24,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			213,200
Average annual operating cost for dry limestone injection			414,400
Thermal effect of dry limestone injection on operating cost of power plant			6,400

	Cost/ton of coal burned, $	Total annual cost, $
Total	4.27	420,800

[a] Basis:

Coal burned–98,500 tons/yr; .788 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $1,036,300
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-58 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
4.64 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	24,400 tons	4.05/ton	98,800
Subtotal raw material			98,800
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	129,300 gal	.11/gal	14,200
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	146,400 kWh	.007/kWh	1,000
Grinding	1,303,000 kWh	.007/kWh	9,100
Injection	234,200 kWh	.007/kWh	1,600
Dust collection (credit)	-176,500 kWh	.007/kWh	(1,200)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			32,100
Dust collection			6,300
Analyses	90 hr	10.00/hr	900
Subtotal conversion costs			136,000
Subtotal direct costs			234,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			225,300
Overhead			
Plant, 20% of conversion costs			27,200
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			258,500
Average annual operating cost for dry limestone injection			493,300
Thermal effect of dry limestone injection on operating cost of power plant			8,300

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.71	501,600

[a] Basis:

Coal burned–293,800 tons/yr; .784 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
O″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $1,280,100
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-59 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
6.20 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	32,700 tons	4.05/ton	132,400
Subtotal raw material			132,400
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	173,300 gal	.11/gal	19,100
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	196,200 kWh	.007/kWh	1,400
Grinding	1,746,200 kWh	.007/kWh	12,200
Injection	313,900 kWh	.007/kWh	2,200
Dust collection (credit)	-173,500 kWh	.007/kWh	(1,200)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			36,100
Dust collection			6,800
Analyses	100 hr	10.00/hr	1,000
Subtotal conversion costs			149,600
Subtotal direct costs			282,000
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			252,000
Overhead			
Plant, 20% of conversion costs			29,900
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			287,900
Average annual operating cost for dry limestone injection			569,900
Thermal effect of dry limestone injection on operating cost of power plant			11,000

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.97	580,900

[a] Basis:

Coal burned–294,300 tons/yr; .785 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,431,500
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-60Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
5.0 Moles CaO Injected per Mole S in Fuel;
7.76 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	40,900 tons	4.05/ton	165,600
Subtotal raw material			165,600
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	216,800 gal	.11/gal	23,800
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	245,400 kWh	.007/kWh	1,700
Grinding	2,184,100 kWh	.007/kWh	15,300
Injection	392,600 kWh	.007/kWh	2,700
Dust collection (credit)	-168,000 kWh	.007/kWh	(1,200)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			39,900
Dust collection			7,200
Analyses	120 hr	10.00/hr	1,200
Subtotal conversion costs			162,600
Subtotal direct costs			328,200
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			276,100
Overhead			
Plant, 20% of conversion costs			32,500
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			314,600
Average annual operating cost for dry limestone injection			642,800
Thermal effect of dry limestone injection on operating cost of power plant			13,800

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.23	656,600

[a] Basis:

Coal burned–294,700 tons/yr; .786 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
O" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,568,800
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection to limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-61 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
6.0 Moles CaO Injected per Mole S in Fuel;
9.33 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	49,100 tons	4.05/ton	198,900
Subtotal raw material			198,900
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	260,200 gal	.11/gal	28,600
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	294,600 kWh	.007/kWh	2,100
Grinding	2,621,900 kWh	.007/kWh	18,400
Injection	471,400 kWh	.007/kWh	3,300
Dust collection (credit)	-165,000 kWh	.007/kWh	(1,200)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			43,300
Dust collection			7,500
Analyses	130 hr	10.00/hr	1,300
Subtotal conversion costs			175,300
Subtotal direct costs			374,200
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			298,200
Overhead			
Plant, 20% of conversion costs			35,100
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			339,300
Average annual operating cost for dry limestone injection			713,500
Thermal effect of dry limestone injection on operating cost of power plant			16,600

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.47	730,100

[a] Basis:

Coal burned–295,100 tons/yr; .787 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
O" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,694,400
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection to limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-62Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
7.0 Moles CaO Injected per Mole S in Fuel;
10.90 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	57,400 tons	4.05/ton	232,500
Subtotal raw material			232,500
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	304,200 gal	.11/gal	33,500
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	344,400 kWh	.007/kWh	2,400
Grinding	3,065,200 kWh	.007/kWh	21,500
Injection	551,000 kWh	.007/kWh	3,900
Dust collection (credit)	-161,500 kWh	.007/kWh	(1,100)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			46,500
Dust collection			7,700
Analyses	150 hr	10.00/hr	1,500
Subtotal conversion costs			187,900
Subtotal direct costs			420,400
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			318,200
Overhead			
Plant, 20% of conversion costs			37,600
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			361,800
Average annual operating cost for dry limestone injection			782,200
Thermal effect of dry limestone injection on operating cost of power plant			19,300

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.71	801,500

[a] Basis:

Coal burned–295,600 tons/yr; .788 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
O" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,808,000
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-63 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
7.73 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	40,700 tons	4.05/ton	164,800
Subtotal raw material			164,800
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	215,700 gal	.11/gal	23,700
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	244,200 kWh	.007/kWh	1,700
Grinding	2,173,400 kWh	.007/kWh	15,200
Injection	390,700 kWh	.007/kWh	2,700
Dust collection (credit)	-294,000 kWh	.007/kWh	(2,100)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			41,000
Dust collection			9,900
Analyses	120 hr	10.00/hr	1,200
Subtotal conversion costs			165,300
Subtotal direct costs			330,100
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			298,300
Overhead			
Plant, 20% of conversion costs			33,100
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			337,400
Average annual operating cost for dry limestone injection			667,500
Thermal effect of dry limestone injection on operating cost of power plant			13,800
		Cost/ton of coal burned, $	Total annual cost, $
Total		1.39	681,300

[a] Basis:

Coal burned–489,700 tons/yr; .784 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
O" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,695,100
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-64 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
10.33 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	54,400 tons	4.05/ton	220,300
Subtotal raw material			220,300
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	288,300 gal	.11/gal	31,700
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	326,400 kWh	.007/kWh	2,300
Grinding	2,905,000 kWh	.007/kWh	20,300
Injection	522,200 kWh	.007/kWh	3,700
Dust collection (credit)	-287,500 kWh	.007/kWh	(2,000)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			45,600
Dust collection			10,400
Analyses	140 hr	10.00/hr	1,400
Subtotal conversion costs			185,400
Subtotal direct costs			405,700
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			328,800
Overhead			
Plant, 20% of conversion costs			37,100
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			371,900
Average annual operating cost for dry limestone injection			777,600
Thermal effect of dry limestone injection on operating cost of power plant			18,400

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.62	796,000

[a] Basis:
Coal burned–490,400 tons/yr; .785 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,868,100
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-65 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
5.0 Moles CaO Injected per Mole S in Fuel;
12.93 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	68,100 tons	4.05/ton	275,800
Subtotal raw material			275,800
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	360,900 gal	.11/gal	39,700
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	408,600 kWh	.007/kWh	2,900
Grinding	3,636,500 kWh	.007/kWh	25,500
Injection	653,800 kWh	.007/kWh	4,600
Dust collection (credit)	-280,000 kWh	.007/kWh	(2,000)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			51,600
Dust collection			11,000
Analyses	160 hr	10.00/hr	1,600
Subtotal conversion costs			206,900
Subtotal direct costs			482,700
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			367,200
Overhead			
Plant, 20% of conversion costs			41,400
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			414,600
Average annual operating cost for dry limestone injection			897,300
Thermal effect of dry limestone injection on operating cost of power plant			23,000

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.87	920,300

[a] Basis:

Coal burned–491,200 tons/yr; .786 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,086,100
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-66 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
6.0 Moles CaO Injected per Mole S in Fuel;
15.55 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	81,900 tons	4.05/ton	331,700
Subtotal raw material			331,700
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	434,100 gal	.11/gal	47,800
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	491,400 kWh	.007/kWh	3,400
Grinding	4,373,500 kWh	.007/kWh	30,600
Injection	786,200 kWh	.007/kWh	5,500
Dust collection (credit)	-275,000 kWh	.007/kWh	(1,900)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying grinding, injection, and solids disposal areas			56,100
Dust collection			11,500
Analyses	180 hr	10.00/hr	1,800
Subtotal conversion costs			226,800
Subtotal direct costs			558,500
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			396,600
Overhead			
Plant, 20% of conversion costs			45,400
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			448,000
Average annual operating cost for dry limestone injection			1,006,500
Thermal effect of dry limestone injection on operating cost of power plant			27,600

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.10	1,034,100

[a] Basis:

Coal burned–491,900 tons/yr; .787 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,253,600
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices. Solids disposed as 15% slurry with no recycle of pond
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-67Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
7.0 Moles CaO Injected per Mole S in Fuel;
18.17 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	95,700 tons	4.05/ton	387,600
Subtotal raw material			387,600
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	507,200 gal	.11/gal	55,800
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	574,200 kWh	.007/kWh	4,000
Grinding	5,110,400 kWh	.007/kWh	35,800
Injection	918,700 kWh	.007/kWh	6,400
Dust collection (credit)	-269,000 kWh	.007/kWh	(1,900)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			60,300
Dust collection			11,900
Analyses	200 hr	10.00/hr	2,000
Subtotal conversion costs			246,300
Subtotal direct costs			633,900
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			423,800
Overhead			
Plant, 20% of conversion costs			49,300
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			479,100
Average annual operating cost for dry limestone injection			1,113,000
Thermal effect of dry limestone injection on operating cost of power plant			32,200

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.32	1,145,200

[a] Basis:

Coal burned–492,600 tons/yr; .788 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,407,700
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-68 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
10.83 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	57,000 tons	4.05/ton	230,900
Subtotal raw material			230,900
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	302,100 gal	.11/gal	33,200
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	342,000 kWh	.007/kWh	2,400
Grinding	3,043,800 kWh	.007/kWh	21,300
Injection	547,200 kWh	.007/kWh	3,800
Dust collection (credit)	-411,600 kWh	.007/kWh	(2,900)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			48,100
Dust collection			12,900
Analyses	150 hr	10.00/hr	1,500
Subtotal conversion costs			192,300
Subtotal direct costs			422,300
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			357,700
Overhead			
Plant, 20% of conversion costs			38,500
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			402,200
Average annual operating cost for dry limestone injection			824,500
Thermal effect of dry limestone injection on operating cost of power plant			19,300

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.23	843,800

[a] Basis:
Coal burned–685,600 tons/yr; .784 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,032,300
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-69 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
14.47 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	76,200 tons	4.05/ton	308,600
Subtotal raw material			308,600
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	403,900 gal	.11/gal	44,400
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	457,200 kWh	.007/kWh	3,200
Grinding	4,069,100 kWh	.007/kWh	28,500
Injection	731,500 kWh	.007/kWh	5,100
Dust collection (credit)	-402,500 kWh	.007/kWh	(2,800)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			54,800
Dust collection			13,600
Analyses	170 hr	10.00/hr	1,700
Subtotal conversion costs			220,500
Subtotal direct costs			529,100
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			401,100
Overhead			
Plant, 20% of conversion costs			44,100
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			451,200
Average annual operating cost for dry limestone injection			980,300
Thermal effect of dry limestone injection on operating cost of power plant			25,700

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.47	1,006,000

[a] Basis:

Coal burned–686,600 tons/yr; .785 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,278,800
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-70 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
5.0 Moles CaO Injected per Mole S in Fuel;
18.11 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	95,300 tons	4.05/ton	386,000
Subtotal raw material			386,000
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	505,100 gal	.11/gal	55,600
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	571,800 kWh	.007/kWh	4,000
Grinding	5,089,000 kWh	.007/kWh	35,600
Injection	914,900 kWh	.007/kWh	6,400
Dust collection (credit)	-392,000 kWh	.007/kWh	(2,700)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			60,700
Dust collection			14,400
Analyses	200 hr	10.00/hr	2,000
Subtotal conversion costs			248,000
Subtotal direct costs			634,000
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			440,600
Overhead			
Plant, 20% of conversion costs			49,600
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			496,200
Average annual operating cost for dry limestone injection			1,130,200
Thermal effect of dry limestone injection on operating cost of power plant			32,200

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.69	1,162,400

[a] Basis:

Coal burned–687,600 tons/yr; .786 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,503,200
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-71 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
6.0 Moles CaO Injected per Mole S in Fuel;
21.77 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	114,600 tons	4.05/ton	464,100
Subtotal raw material			464,100
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	607,400 gal	.11/gal	66,800
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	687,600 kWh	.007/kWh	4,800
Grinding	6,119,600 kWh	.007/kWh	42,800
Injection	1,100,200 kWh	.007/kWh	7,700
Dust collection (credit)	-385,000 kWh	.007/kWh	(2,700)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			66,200
Dust collection			15,000
Analyses	220 hr	10.00/hr	2,200
Subtotal conversion costs			274,800
Subtotal direct costs			738,900
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			476,600
Overhead			
Plant, 20% of conversion costs			55,000
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			537,600
Average annual operating cost for dry limestone injection			1,276,500
Thermal effect of dry limestone injection on operating cost of power plant			38,600

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.91	1,315,100

[a] Basis:

Coal burned–688,600 tons/yr; .787 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,707,700
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

TableA-72 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 0.8% S in fuel;
7.0 Moles CaO Injected per Mole S in Fuel;
25.43 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	133,900 tons	4.05/ton	542,300
Subtotal raw material			542,300
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	709,700 gal	.11/gal	78,100
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	803,400 kWh	.007/kWh	5,600
Grinding	7,150,300 kWh	.007/kWh	50,100
Injection	1,285,400 kWh	.007/kWh	9,000
Dust collection (credit)	-376,600 kWh	.007/kWh	(2,600)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			71,300
Dust collection			15,500
Analyses	240 hr	10.00/hr	2,400
Subtotal conversion costs			311,300
Subtotal direct costs			853,600
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			509,200
Overhead			
Plant, 20% of conversion costs			62,300
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			578,500
Average annual operating cost for dry limestone injection			1,432,100
Thermal effect of dry limestone injection on operating cost of power plant			45,000

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.14	1,477,100

[a] Basis:
Coal burned–689,600 tons/yr; .788 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
O″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $2,893,300
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-73 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
1.93 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	10,200 tons	4.05/ton	41,300
Subtotal raw material			41,300
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	54,100 gal	.11/gal	6,000
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	61,200 kWh	.007/kWh	400
Grinding	544,700 kWh	.007/kWh	3,800
Injection	97,000 kWh	.007/kWh	700
Dust collection (credit)	-57,000 kWh	.007/kWh	(400)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			21,700
Dust collection			2,800
Analyses	50 hr	10.00/hr	500
Subtotal conversion costs			107,500
Subtotal direct costs			148,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			143,800
Overhead			
Plant, 20% of conversion costs			21,500
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			171,300
Average annual operating cost for dry limestone injection			320,100
Thermal effect of dry limestone injection on operating cost of power plant			3,000

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.30	323,100

[a] Basis:

Coal burned–98,000 tons/yr; .784 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $817,100
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-74 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
3.89 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	20,500 tons	4.05/ton	83,000
Subtotal raw material			83,000
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	108,700 gal	.11/gal	12,000
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	123,000 kWh	.007/kWh	900
Grinding	1,094,700 kWh	.007/kWh	7,700
Injection	196,800 kWh	.007/kWh	1,400
Dust collection (credit)	-52,500 kWh	.007/kWh	(400)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			28,800
Dust collection			3,300
Analyses	80 hr	10.00/hr	800
Subtotal conversion costs			126,500
Subtotal direct costs			209,500
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			188,400
Overhead			
Plant, 20% of conversion costs			25,300
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			219,700
Average annual operating cost for dry limestone injection			429,200
Thermal effect of dry limestone injection on operating cost of power plant			5,900

	Cost/ton of coal burned, $	Total annual cost, $
Total	4.42	435,100

[a] Basis:

Coal burned–98,400 tons/yr; .788 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,070,500
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-75 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
5.87 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	30,900 tons	4.05/ton	125,100
Subtotal raw material			125,100
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	163,800 gal	.11/gal	18,000
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	185,400 kWh	.007/kWh	1,300
Grinding	1,650,100 kWh	.007/kWh	11,600
Injection	296,600 kWh	.007/kWh	2,100
Dust collection (credit)	-48,800 kWh	.007/kWh	(300)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			34,400
Dust collection			3,700
Analyses	100 hr	10.00/hr	1,000
Subtotal conversion costs			143,800
Subtotal direct costs			268,900
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			223,800
Overhead			
Plant, 20% of conversion costs			28,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			258,600
Average annual operating cost for dry limestone injection			527,500
Thermal effect of dry limestone injection on operating cost of power plant			8,900

	Cost/ton of coal burned, $	Total annual cost, $
Total	5.42	536,400

[a] Basis:

Coal burned–98,900 tons/yr; .791 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,271,500
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-76 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
7.86 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	41,400 tons	4.05/ton	167,700
Subtotal raw material			167,700
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	219,400 gal	.11/gal	24,100
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	248,400 kWh	.007/kWh	1,700
Grinding	2,210,800 kWh	.007/kWh	15,500
Injection	379,400 kWh	.007/kWh	2,700
Dust collection (credit)	-46,000 kWh	.007/kWh	(300)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			39,300
Dust collection			4,000
Analyses	120 hr	10.00/hr	1,200
Subtotal conversion costs			160,200
Subtotal direct costs			327,900
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			253,800
Overhead			
Plant, 20% of conversion costs			32,000
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			291,800
Average annual operating cost for dry limestone injection			619,700
Thermal effect of dry limestone injection on operating cost of power plant			12,000

	Cost/ton of coal burned, $	Total annual cost, $
Total	6.36	631,700

[a] Basis:
Coal burned–99,400 tons/yr; .795 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $1,442,000
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-77 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
5.80 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	30,600 tons	4.05/ton	123,900
Subtotal raw material			123,900
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	162,200 gal	.11/gal	17,800
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	183,600 kWh	.007/kWh	1,300
Grinding	1,634,000 kWh	.007/kWh	11,400
Injection	293,800 kWh	.007/kWh	2,100
Dust collection (credit)	-171,000 kWh	.007/kWh	(1,200)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			35,200
Dust collection			6,900
Analyses	100 hr	10.00/hr	1,000
Subtotal conversion costs			146,500
Subtotal direct costs			270,400
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			247,200
Overhead			
Plant, 20% of conversion costs			29,300
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			282,500
Average annual operating cost for dry limestone injection			552,900
Thermal effect of dry limestone injection on operating cost of power plant			8,900

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.91	561,800

[a] Basis:

Coal burned – 293,900 tons/yr; .784 lbs/kWh
Remaining life of power plant – 15 yr
Power plant on-stream time – 5000 hr/yr
Midwest plant location – 1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,404,600
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-78Average Annual Operating Cost for Reducing SO_3 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
11.67 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	61,400 tons	4.05/ton	248,700
Subtotal raw material			248,700
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	325,400 gal	.11/gal	35,800
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	368,400 kWh	.007/kWh	2,600
Grinding	3,278,800 kWh	.007/kWh	23,000
Injection	589,400 kWh	.007/kWh	4,100
Dust collection (credit)	-157,500 kWh	.007/kWh	(1,100)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			48,100
Dust collection			8,100
Analyses	150 hr	10.00/hr	1,500
Subtotal conversion costs			194,100
Subtotal direct costs			442,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			329,900
Overhead			
Plant, 20% of conversion costs			38,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			374,700
Average annual operating cost for dry limestone injection			817,500
Thermal effect of dry limestone injection on operating cost of power plant			17,700

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.83	835,200

[a] Basis:

Coal burned–295,300 tons/yr; .788 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,874,200
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

TableA-79 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
17.60 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	92,700 tons	4.05/ton	375,400
Subtotal raw material			375,400
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	491,300 gal	.11/gal	54,000
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	556,200 kWh	.007/kWh	3,900
Grinding	4,950,200 kWh	.007/kWh	34,700
Injection	889,900 kWh	.007/kWh	6,200
Dust collection (credit)	-146,500 kWh	.007/kWh	(1,000)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			58,400
Dust collection			9,100
Analyses	190 hr	10.00/hr	1,900
Subtotal conversion costs			239,200
Subtotal direct costs			614,600
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			396,200
Overhead			
Plant, 20% of conversion costs			47,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			450,000
Average annual operating cost for dry limestone injection			1,064,600
Thermal effect of dry limestone injection on operating cost of power plant			26,800

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.68	1,091,400

[a] Basis:
Coal burned–296,800 tons/yr; .791 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,251,400
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-80 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
23.59 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	124,200 tons	4.05/ton	503,000
Subtotal raw material			503,000
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	658,300 gal	.11/gal	72,400
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	745,200 kWh	.007/kWh	5,200
Grinding	6,632,300 kWh	.007/kWh	46,400
Injection	1,192,300 kWh	.007/kWh	8,300
Dust collection (credit)	-138,000 kWh	.007/kWh	(1,000)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			67,400
Dust collection			9,800
Analyses	230 hr	10.00/hr	2,300
Subtotal conversion costs			282,800
Subtotal direct costs			785,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			453,100
Overhead			
Plant, 20% of conversion costs			56,600
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			515,700
Average annual operating cost for dry limestone injection			1,301,500
Thermal effect of dry limestone injection on operating cost of power plant			35,800

	Cost/ton of coal burned, $	Total annual cost, $
Total	4.48	1,337,300

[a] Basis:

Coal burned–298,200 tons/yr; .795 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,574,200
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-81 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250 MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
9.67 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	50,900 tons	4.05/ton	206,100
Subtotal raw material			206,100
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	269,800 gal	.11/gal	29,700
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	305,400 kWh	.007/kWh	2,100
Grinding	2,718,100 kWh	.007/kWh	19,000
Injection	488,600 kWh	.007/kWh	3,400
Dust collection (credit)	-285,000 kWh	.007/kWh	(2,000)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			45,400
Dust collection			10,600
Analyses	140 hr	10.00/hr	1,400
Subtotal conversion costs			181,600
Subtotal direct costs			387,700
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			328,300
Overhead			
Plant, 20% of conversion costs			36,300
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			370,600
Average annual operating cost for dry limestone injection			758,300
Thermal effect of dry limestone injection on operating cost of power plant			14,800

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.58	773,100

[a] Basis:

Coal burned – 489,900 tons/yr; .784 lbs/kWh
Remaining life of power plant – 15 yr
Power plant on-stream time – 5000 hr/yr
Midwest plant location – 1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,865,600
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-82 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
19.45 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	102,400 tons	4.05/ton	414,700
Subtotal raw material			414,700
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	542,700 gal	.11/gal	59,700
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	614,400 kWh	.007/kWh	4,300
Grinding	5,468,200 kWh	.007/kWh	38,300
Injection	983,000 kWh	.007/kWh	6,900
Dust collection (credit)	-262,500 kWh	.007/kWh	(1,800)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			62,500
Dust collection			12,500
Analyses	210 hr	10.00/hr	2,100
Subtotal conversion costs			256,500
Subtotal direct costs			671,200
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			439,800
Overhead			
Plant, 20% of conversion costs			51,300
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			497,100
Average annual operating cost for dry limestone injection			1,168,300
Thermal effect of dry limestone injection on operating cost of power plant			29,500

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.43	1,197,800

[a] Basis:

Coal burned–492,200 tons/yr; .788 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,498,900
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-83 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
29.33 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	154,400 tons	4.05/ton	625,300
Subtotal raw material			625,300
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	818,300 gal	.11/gal	90,000
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	926,400 kWh	.007/kWh	6,500
Grinding	8,245,000 kWh	.007/kWh	57,700
Injection	1,482,200 kWh	.007/kWh	10,400
Dust collection (credit)	-244,000 kWh	.007/kWh	(1,700)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			76,300
Dust collection			14,000
Analyses	260 hr	10.00/hr	2,600
Subtotal conversion costs			337,700
Subtotal direct costs			963,000
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			530,000
Overhead			
Plant, 20% of conversion costs			67,500
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			604,500
Average annual operating cost for dry limestone injection			1,567,500
Thermal effect of dry limestone injection on operating cost of power plant			44,600
	Cost/ton of coal burned, $		Total annual cost, $
Total	3.26		1,612,100

[a] Basis:

Coal burned – 494,600 tons/yr; .791 lbs/kWh
Remaining life of power plant – 15 yr
Power plant on-stream time – 5000 hr/yr
Midwest plant location – 1972 costs
0″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $3,011,400
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-84 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
39.32 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	207,000 tons	4.05/ton	838,400
Subtotal raw material			838,400
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	1,097,100 gal	.11/gal	120,700
Sluice water	390,000 M gal	.03/M gal	11,700
Electricity			
Receiving-drying	1,242,000 kWh	.007/kWh	8,700
Grinding	11,053,800 kWh	.007/kWh	77,400
Injection	1,987,200 kWh	.007/kWh	13,900
Dust collection (credit)	-230,000 kWh	.007/kWh	(1,600)
Solids disposal	750,800 kWh	.007/kWh	5,300
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			89,800
Dust collection			15,100
Analyses	320 hr	10.00/hr	3,200
Subtotal conversion costs			414,500
Subtotal direct costs			1,252,900
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			615,600
Overhead			
Plant, 20% of conversion costs			82,900
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			705,500
Average annual operating cost for dry limestone injection			1,958,400
Thermal effect of dry limestone injection on operating cost of power plant			59,700

	Cost/ton of coal burned, $	Total annual cost, $
Total	4.06	2,018,100

[a] Basis:

Coal burned—497,000 tons/yr; .795 lbs/kWh
Remaining life of power plant—15 yr
Power plant on-stream time—5000 hr/yr
Midwest plant location—1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $3,498,000
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-85 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
13.53 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	71,200 tons	4.05/ton	288,400
Subtotal raw material			288,400
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	377,400 gal	.11/gal	41,500
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	427,200 kWh	.007/kWh	3,000
Grinding	3,802,100 kWh	.007/kWh	26,600
Injection	683,500 kWh	.007/kWh	4,800
Dust collection (credit)	-399,000 kWh	.007/kWh	(2,800)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			53,400
Dust collection			13,800
Analyses	170 hr	10.00/hr	1,700
Subtotal conversion costs			214,000
Subtotal direct costs			502,400
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			394,000
Overhead			
Plant, 20% of conversion costs			42,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			442,800
Average annual operating cost for dry limestone injection			945,200
Thermal effect of dry limestone injection on operating cost of power plant			20,700

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.41	965,900

[a] Basis:

Coal burned–685,800 tons/yr; .784 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,238,600
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-86 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
27.23 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	143,300 tons	4.05/ton	580,400
Subtotal raw material			580,400
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	759,500 gal	.11/gal	83,500
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	859,800 kWh	.007/kWh	6,000
Grinding	7,652,200 kWh	.007/kWh	53,600
Injection	1,375,700 kWh	.007/kWh	9,600
Dust collection (credit)	-367,500 kWh	.007/kWh	(2,600)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			74,000
Dust collection			16,200
Analyses	250 hr	10.00/hr	2,500
Subtotal conversion costs			324,700
Subtotal direct costs			905,100
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			529,000
Overhead			
Plant, 20% of conversion costs			65,000
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			601,000
Average annual operating cost for dry limestone injection			1,506,100
Thermal effect of dry limestone injection on operating cost of power plant			41,300

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.25	1,547,400

[a] Basis:

Coal burned–689,100 tons/yr; .788 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $3,005,900
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-87 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
41.07 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	216,200 tons	4.05/ton	875,600
Subtotal raw material			875,600
Conversion costs			
Operating labor & supervision including payroll overhead	13,370 man-hr	6.00/man-hr	80,200
Utilities[b]			
Fuel oil (drying)	1,145,900 gal	.11/gal	126,000
Sluice water	390,000 M gal	.03/M gal	11,700
Electricity			
Receiving-drying	1,297,200 kWh	.007/kWh	9,100
Grinding	11,545,100 kWh	.007/kWh	80,800
Injection	2,075,500 kWh	.007/kWh	14,500
Dust collection (credit)	-341,600 kWh	.007/kWh	(2,400)
Solids disposal	750,800 kWh	.007/kWh	5,300
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			92,100
Dust collection			18,200
Analyses	390 hr	10.00/hr	3,900
Subtotal conversion costs			439,400
Subtotal direct costs			1,315,000
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			647,100
Overhead			
Plant, 20% of conversion costs			87,900
Administrative, 10% of operating labor			8,000
Subtotal indirect costs			743,000
Average annual operating cost for dry limestone injection			2,058,000
Thermal effect of dry limestone injection on operating cost of power plant			62,500

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.06	2,120,500

[a] Basis:

Coal burned–692,400 tons/yr; .791 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $3,676,800
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-88 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 3.0% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
55.04 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	289,700 tons	4.05/ton	1,173,300
Subtotal raw material			1,173,300
Conversion costs			
Operating labor & supervision including payroll overhead	13,370 man-hr	6.00/man-hr	80,200
Utilities[b]			
Fuel oil (drying)	1,535,400 gal	.11/gal	168,900
Sluice water	570,000 M gal	.03/M gal	17,100
Electricity			
Receiving-drying	1,738,200 kWh	.007/kWh	12,200
Grinding	15,470,000 kWh	.007/kWh	108,300
Injection	2,781,100 kWh	.007/kWh	19,500
Dust collection (credit)	-322,000 kWh	.007/kWh	(2,300)
Solids disposal	1,097,300 kWh	.007/kWh	7,700
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			108,200
Dust collection			19,700
Analyses	390 hr	10.00/hr	3,900
Subtotal conversion costs			543,400
Subtotal direct costs			1,716,700
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			750,100
Overhead			
Plant, 20% of conversion costs			108,700
Administrative, 10% of operating labor			8,000
Subtotal indirect costs			866,800
Average annual operating cost for dry limestone injection			2,583,500
Thermal effect of dry limestone injection on operating cost of power plant			83,600

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.83	2,667,100

[a] Basis:

Coal burned–695,800 tons/yr; .795 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $4,262,100
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-89 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
3.2 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	17,000 tons	4.05/ton	68,900
Subtotal raw material			68,900
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	90,100 gal	.11/gal	9,900
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	102,000 kWh	.007/kWh	700
Grinding	907,800 kWh	.007/kWh	6,400
Injection	163,200 kWh	.007/kWh	1,100
Dust collection (credit)	-53,500 kWh	.007/kWh	(400)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			26,700
Dust collection			3,200
Analyses	70 hr	10.00/hr	700
Subtotal conversion costs			120,300
Subtotal direct costs			189,200
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			175,200
Overhead			
Plant, 20% of conversion costs			24,000
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			205,200
Average annual operating cost for dry limestone injection			394,400
Thermal effect of dry limestone injection on operating cost of power plant			4,900

	Cost/ton of coal burned, $	Total annual cost, $
Total	4.06	399,300

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[a] Basis:

Coal burned–98,300 tons/yr; .786 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $995,300
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-90 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
6.5 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	34,400 tons	4.05/ton	139,300
Subtotal raw material			139,300
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	182,300 gal	.11/gal	20,100
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	206,400 kWh	.007/kWh	1,400
Grinding	1,837,000 kWh	.007/kWh	12,900
Injection	330,200 kWh	.007/kWh	2,300
Dust collection (credit)	-47,300 kWh	.007/kWh	(300)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			36,200
Dust collection			3,800
Analyses	110 hr	10.00/hr	1,100
Subtotal conversion costs			149,500
Subtotal direct costs			288,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			234,600
Overhead			
Plant, 20% of conversion costs			29,900
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			270,500
Average annual operating cost for dry limestone injection			559,300
Thermal effect of dry limestone injection on operating cost of power plant			10,000

	Cost/ton of coal burned, $	Total annual cost, $
Total	5.74	569,300

[a] Basis:

Coal burned–99,100 tons/yr; .793 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,332,900
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-91 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
9.9 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	52,100 tons	4.05/ton	211,000
Subtotal raw material			211,000
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	276,100 gal	.11/gal	30,400
Sluice water	267,100 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	312,600 kWh	.007/kWh	2,200
Grinding	2,782,100 kWh	.007/kWh	19,500
Injection	500,200 kWh	.007/kWh	3,500
Dust collection (credit)	-42,700 kWh	.007/kWh	(300)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			43,800
Dust collection			4,300
Analyses	140 hr	10.00/hr	1,400
Subtotal conversion costs			176,800
Subtotal direct costs			387,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			282,100
Overhead			
Plant, 20% of conversion costs			35,400
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			323,500
Average annual operating cost for dry limestone injection			711,300
Thermal effect of dry limestone injection on operating cost of power plant			15,100

	Cost/ton of coal burned, $	Total annual cost, $
Total	7.27	726,400

[a] Basis:

Coal burned–99,900 tons/yr; .799 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,602,600
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-92 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(50-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
13.3 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	70,200 tons	4.05/ton	284,300
Subtotal raw material			284,300
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	372,100 gal	.11/gal	40,900
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	421,200 kWh	.007/kWh	2,900
Grinding	3,748,700 kWh	.007/kWh	26,200
Injection	673,900 kWh	.007/kWh	4,700
Dust collection (credit)	-38,500 kWh	.007/kWh	(300)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			50,400
Dust collection			4,800
Analyses	160 hr	10.00/hr	1,600
Subtotal conversion costs			203,200
Subtotal direct costs			487,500
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			323,600
Overhead			
Plant, 20% of conversion costs			40,700
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			370,300
Average annual operating cost for dry limestone injection			857,800
Thermal effect of dry limestone injection on operating cost of power plant			20,200

	Cost/ton of coal burned, $	Total annual cost, $
Total	8.72	878,000

[a] Basis:

Coal burned–100,700 tons/yr; .806 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $1,838,700
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-93 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
9.7 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	51,100 tons	4.05/ton	207,000
Subtotal raw material			207,000
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	270,800 gal	.11/gal	29,800
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	306,600 kWh	.007/kWh	2,100
Grinding	2,728,700 kWh	.007/kWh	19,100
Injection	490,600 kWh	.007/kWh	3,400
Dust collection (credit)	-160,500 kWh	.007/kWh	(1,100)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			44,300
Dust collection			7,800
Analyses	140 hr	10.00/hr	1,400
Subtotal conversion costs			178,800
Subtotal direct costs			385,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			305,600
Overhead			
Plant, 20% of conversion costs			35,800
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			347,400
Average annual operating cost for dry limestone injection			733,200
Thermal effect of dry limestone injection on operating cost of power plant			14,800

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.54	748,000

[a] Basis:

Coal burned—294,800 tons/yr; .786 lbs/kWh
Remaining life of power plant—15 yr
Power plant on-stream time—5000 hr/yr
Midwest plant location—1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital 6investment, $1,736,200
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

TableA-94 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
19.6 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	103,100 tons	4.05/ton	417,600
Subtotal raw material			417,600
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	546,400 gal	.11/gal	60,100
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	618,600 kWh	.007/kWh	4,300
Grinding	5,505,500 kWh	.007/kWh	38,500
Injection	989,800 kWh	.007/kWh	6,900
Dust collection (credit)	-142,000 kWh	.007/kWh	(1,000)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			61,600
Dust collection			9,500
Analyses	140 hr	10.00/hr	1,400
Subtotal conversion costs			253,300
Subtotal direct costs			670,900
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			417,000
Overhead			
Plant, 20% of conversion costs			50,700
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			473,700
Average annual operating cost for dry limestone injection			1,144,600
Thermal effect of dry limestone injection on operating cost of power plant			29,900

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.95	1,174,500

[a] Basis:

Coal burned–297,300 tons/yr; .793 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $2,369,500
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-95 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
29.7 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	156,000 tons	4.05/ton	631,800
Subtotal raw material			631,800
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	827,300 gal	.11/gal	91,000
Sluice water	390,000 M gal	.03/M gal	11,700
Electricity			
Receiving-drying	936,600 kWh	.007/kWh	6,600
Grinding	8,335,700 kWh	.007/kWh	58,300
Injection	1,498,600 kWh	.007/kWh	10,500
Dust collection (credit)	-128,000 kWh	.007/kWh	(900)
Solids disposal	750,800 kWh	.007/kWh	5,300
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			77,100
Dust collection			10,700
Analyses	270 hr	10.00/hr	2,700
Subtotal conversion costs			343,300
Subtotal direct costs			975,100
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			515,100
Overhead			
Plant, 20% of conversion costs			68,700
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			590,800
Average annual operating cost for dry limestone injection			1,565,900
Thermal effect of dry limestone injection on operating cost of power plant			45,100

	Cost/ton of coal burned, $	Total annual cost, $
Total	5.38	1,611,000

[a] Basis:

Coal burned–299,700 tons/yr; .799 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $2,926,600
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-96 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(150-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
40 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	210,500 tons	4.05/ton	852,500
Subtotal raw material			852,500
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	1,115,700 gal	.11/gal	122,700
Sluice water	390,000 M gal	.03/M gal	11,700
Electricity			
Receiving-drying	1,263,000 kWh	.007/kWh	8,800
Grinding	11,240,700 kWh	.007/kWh	78,700
Injection	2,020,800 kWh	.007/kWh	14,100
Dust collection (credit)	-115,500 kWh	.007/kWh	(800)
Solids disposal	750,800 kWh	.007/kWh	5,300
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			89,500
Dust collection			11,800
Analyses	320 hr	10.00/hr	3,200
Subtotal conversion costs			415,300
Subtotal direct costs			1,267,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			594,200
Overhead			
Plant, 20% of conversion costs			83,100
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			684,300
Average annual operating cost for dry limestone injection			1,952,100
Thermal effect of dry limestone injection on operating cost of power plant			60,700

	Cost/ton of coal burned, $	Total annual cost, $
Total	6.66	2,012,800

[a] Basis:
Coal burned–302,100 tons/yr; .806 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $3,376,200
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-97 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
16.8 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	85,100 tons	4.05/ton	344,700
Subtotal raw material			344,700
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	451,000 gal	.11/gal	49,600
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	510,600 kWh	.007/kWh	3,600
Grinding	4,544,300 kWh	.007/kWh	31,800
Injection	817,000 kWh	.007/kWh	5,700
Dust collection (credit)	-267,500 kWh	.007/kWh	(1,900)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			57,300
Dust collection			12,100
Analyses	190 hr	10.00/hr	1,900
Subtotal conversion costs			232,100
Subtotal direct costs			576,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			407,400
Overhead			
Plant, 20% of conversion costs			46,400
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			459,800
Average annual operating cost for dry limestone injection			1,036,600
Thermal effect of dry limestone injection on operating cost of power plant			24,600

	Cost/ton of coal burned, $	Total annual cost, $
Total	2.16	1,061,200

[a] Basis:

Coal burned–491,400 tons/yr; .786 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $2,314,500
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-98 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
32.7 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	171,900 tons	4.05/ton	696,200
Subtotal raw material			696,200
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	911,100 gal	.11/gal	100,200
Sluice water	390,000 M gal	.03/M gal	11,700
Electricity			
Receiving-drying	1,031,400 kWh	.007/kWh	7,200
Grinding	9,179,500 kWh	.007/kWh	64,300
Injection	1,650,200 kWh	.007/kWh	11,600
Dust collection (credit)	-236,500 kWh	.007/kWh	(1,700)
Solids disposal	750,800 kWh	.007/kWh	5,300
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			82,000
Dust collection			14,600
Analyses	280 hr	10.00/hr	2,800
Subtotal conversion costs			368,300
Subtotal direct costs			1,064,500
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			566,900
Overhead			
Plant, 20% of conversion costs			73,700
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			647,600
Average annual operating cost for dry limestone injection			1,712,100
Thermal effect of dry limestone injection on operating cost of power plant			49,900

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.56	1,762,000

[a] Basis:

Coal burned–495,400 tons/yr; .793 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $3,221,100
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

TableA-99 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
49.4 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	260,200 tons	4.05/ton	1,053,800
Subtotal raw material			1,053,800
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	1,379,100 gal	.11/gal	151,700
Sluice water	570,000 M gal	.03/M gal	17,100
Electricity			
Receiving-drying	1,561,200 kWh	.007/kWh	10,900
Grinding	13,894,700 kWh	.007/kWh	97,300
Injection	2,497,900 kWh	.007/kWh	17,500
Dust collection (credit)	-213,500 kWh	.007/kWh	(1,500)
Solids disposal	1,097,300 kWh	.007/kWh	7,700
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			102,600
Dust collection			16,500
Analyses	360 hr	10.00/hr	3,600
Subtotal conversion costs			493,700
Subtotal direct costs			1,547,500
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			698,400
Overhead			
Plant, 20% of conversion costs			98,700
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			804,100
Average annual operating cost for dry limestone injection			2,351,600
Thermal effect of dry limestone injection on operating cost of power plant			75,200

	Cost/ton of coal burned, $	Total annual cost, $
Total	4.86	2,426,800

[a] Basis:

Coal burned–499,400 tons/yr; .799 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $3,968,400
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-100 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(250-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
66.7 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	350,800 tons	4.05/ton	1,420,700
Subtotal raw material			1,420,700
Conversion costs			
Operating labor & supervision including payroll overhead	13,370 man-hr	6.00/man-hr	80,200
Utilities[b]			
Fuel oil (drying)	1,859,200 gal	.11/gal	204,500
Sluice water	609,000 M gal	.03/M gal	18,300
Electricity			
Receiving-drying	2,104,800 kWh	.007/kWh	14,700
Grinding	18,732,700 kWh	.007/kWh	131,100
Injection	3,367,700 kWh	.007/kWh	23,600
Dust collection (credit)	-192,500 kWh	.007/kWh	(1,300)
Solids disposal	1,172,300 kWh	.007/kWh	8,200
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			119,300
Dust collection			18,200
Analyses	430 hr	10.00/hr	4,300
Subtotal conversion costs			621,100
Subtotal direct costs			2,041,800
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			806,400
Overhead			
Plant, 20% of conversion costs			124,200
Administrative, 10% of operating labor			8,000
Subtotal indirect costs			938,600
Average annual operating cost for dry limestone injection			2,980,400
Thermal effect of dry limestone injection on operating cost of power plant			101,100

	Cost/ton of coal burned, $	Total annual cost, $
Total	6.12	3,081,500

[a] Basis:

Coal burned – 503,500 tons/yr; .806 lbs/kWh
Remaining life of power plant – 15 yr
Power plant on-stream time – 5000 hr/yr
Midwest plant location – 1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $4,582,000
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-101 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
1.0 Moles CaO Injected per Mole S in Fuel;
22.7 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	119,100 tons	4.05/ton	482,400
Subtotal raw material			482,400
Conversion costs			
Operating labor & supervision including payroll overhead	10,070 man-hr	6.00/man-hr	60,400
Utilities[b]			
Fuel oil (drying)	631,200 gal	.11/gal	69,400
Sluice water	267,000 M gal	.03/M gal	8,000
Electricity			
Receiving-drying	714,600 kWh	.007/kWh	5,000
Grinding	6,359,900 kWh	.007/kWh	44,500
Injection	1,143,400 kWh	.007/kWh	8,000
Dust collection (credit)	-374,500 kWh	.007/kWh	(2,600)
Solids disposal	514,000 kWh	.007/kWh	3,600
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			67,800
Dust collection			15,700
Analyses	230 hr	10.00/hr	2,300
Subtotal conversion costs			282,100
Subtotal direct costs			764,500
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			489,800
Overhead			
Plant, 20% of conversion costs			56,400
Administrative, 10% of operating labor			6,000
Subtotal indirect costs			552,200
Average annual operating cost for dry limestone injection			1,316,700
Thermal effect of dry limestone injection on operating cost of power plant			34,500

	Cost/ton of coal burned, $	Total annual cost, $
Total	1.96	1,351,200

[a] Basis:
Coal burned–688,000 tons/yr; .786 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $2,782,700
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-102 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
2.0 Moles CaO Injected per Mole S in Fuel;
45.8 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	240,600 tons	4.05/ton	974,400
Subtotal raw material			974,400
Conversion costs			
Operating labor & supervision including payroll overhead	11,720 man-hr	6.00/man-hr	70,300
Utilities[b]			
Fuel oil (drying)	1,275,200 gal	.11/gal	140,300
Sluice water	570,000 M gal	.03/M gal	17,100
Electricity			
Receiving-drying	1,443,600 kWh	.007/kWh	10,100
Grinding	12,848,000 kWh	.007/kWh	89,900
Injection	2,309,800 kWh	.007/kWh	16,200
Dust collection (credit)	-331,100 kWh	.007/kWh	(2,300)
Solids disposal	1,097,300 kWh	.007/kWh	7,700
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			98,800
Dust collection			19,000
Analyses	340 hr	10.00/hr	3,400
Subtotal conversion costs			470,500
Subtotal direct costs			1,444,900
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			691,200
Overhead			
Plant, 20% of conversion costs			94,100
Administrative, 10% of operating labor			7,000
Subtotal indirect costs			792,300
Average annual operating cost for dry limestone injection			2,237,200
Thermal effect of dry limestone injection on operating cost of power plant			69,800

	Cost/ton of coal burned, $	Total annual cost, $
Total	3.33	2,307,000

[a] Basis:

Coal burned—693,600 tons/yr; .793 lbs/kWh
Remaining life of power plant—15 yr
Power plant on-stream time—5000 hr/yr
Midwest plant location—1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $3,927,000
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-103 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
3.0 Moles CaO Injected per Mole S in Fuel;
69.2 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	364,300 tons	4.05/ton	1,475,400
Subtotal raw material			1,475,400
Conversion costs			
Operating labor & supervision including payroll overhead	13,370 man-hr	6.00/man-hr	80,200
Utilities[b]			
Fuel oil (drying)	1,930,800 gal	.11/gal	212,400
Sluice water	630,000 M gal	.03/M gal	18,900
Electricity			
Receiving-drying	2,185,800 kWh	.007/kWh	15,300
Grinding	19,453,600 kWh	.007/kWh	136,200
Injection	3,497,300 kWh	.007/kWh	24,500
Dust collection (credit)	-298,900 kWh	.007/kWh	(2,100)
Solids disposal	1,212,800 kWh	.007/kWh	8,500
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			121,500
Dust collection			21,500
Analyses	440 hr	10.00/hr	4,400
Subtotal conversion costs			641,300
Subtotal direct costs			2,116,700
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			840,600
Overhead			
Plant, 20% of conversion costs			128,300
Administrative, 10% of operating labor			8,000
Subtotal indirect costs			976,900
Average annual operating cost for dry limestone injection			3,093,600
Thermal effect of dry limestone injection on operating cost of power plant			105,200

	Cost/ton of coal burned, $	Total annual cost, $
Total	4.57	3,198,800

[a] Basis:
Coal burned–699,200 tons/yr; .799 lbs/kWh
Remaining life of power plant–15 yr
Power plant on-stream time–5000 hr/yr
Midwest plant location–1972 costs
0" x 1½" limestone ground to 80% minus 400 mesh
Capital investment, $4,766,400
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-104 Average Annual Operating Cost for Reducing SO_2 Emission from Power Plants by Dry Limestone Injection—Regulated Power Company Economics[a]

(350-MW Existing Coal-Fired Power Unit; 5.0% S in fuel;
4.0 Moles CaO Injected per Mole S in Fuel;
93.3 Tons Dry Limestone per Hour)

	Annual quantity	Unit cost, $	Total annual cost, $
Direct Costs			
Delivered raw material			
Limestone (95% $CaCO_3$)	491,100 tons	4.05/ton	1,989,000
Subtotal raw material			1,989,000
Conversion costs			
Operating labor & supervision including payroll overhead	15,350 man-hr	6.00/man-hr	92,100
Utilities[b]			
Fuel oil (drying)	2,602,800 gal	.11/gal	286,300
Sluice water	831,000 M gal	.03/M gal	24,900
Electricity			
Receiving-drying	2,946,600 kWh	.007/kWh	20,600
Grinding	26,224,700 kWh	.007/kWh	183,600
Injection	4,714,600 kWh	.007/kWh	33,000
Dust collection (credit)	-269,500 kWh	.007/kWh	(1,900)
Solids disposal	1,599,700 kWh	.007/kWh	11,200
Maintenance			
Labor and material			
Drying, grinding, injection, and solids disposal areas			145,700
Dust collection			23,700
Analyses	530 hr	10.00/hr	5,300
Subtotal conversion costs			824,500
Subtotal direct costs			2,813,500
Indirect Costs			
Average capital charges at 17.6% of initial fixed investment			993,600
Overhead			
Plant, 20% of conversion costs			164,900
Administrative, 10% of operating labor			9,200
Subtotal indirect costs			1,167,700
Average annual operating cost for dry limestone injection			3,981,200
Thermal effect of dry limestone injection on operating cost of power plant			141,500

	Cost/ton of coal burned, $	Total annual cost, $
Total	5.85	4,122,700

[a] Basis:

Coal burned – 705,000 tons/yr; .806 lbs/kWh
Remaining life of power plant – 15 yr
Power plant on-stream time – 5000 hr/yr
Midwest plant location – 1972 costs
0″ x 1½″ limestone ground to 80% minus 400 mesh
Capital investment, $5,645,500
Incremental electrostatic precipitator added to maintain dust emission rate prior to injection of limestone. Dust collection efficiency prior to injection of limestone is assumed to be 99% using a combination of mechanical and electrostatic devices.
Solids disposed as 15% slurry with no recycle of pond water.
Disposal pond located 1 mile from power unit.
Cost of solids disposal pond not included.

[b] Cost of utility supplied from power plant at full value.

Table A-105

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 751500

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	97900	376200	376200
17	5000	250000	97900	365800	742000
18	5000	250000	97900	355400	1097400
19	5000	250000	97900	344900	1442300
20	5000	250000	97900	334500	1776800
21	3500	175000	68600	288000	2064800
22	3500	175000	68600	277600	2342400
23	3500	175000	68600	267200	2609600
24	3500	175000	68600	256700	2866300
25	3500	175000	68600	246300	3112600
26	1500	75000	29400	180200	3292800
27	1500	75000	29400	169800	3462600
28	1500	75000	29400	159400	3622000
29	1500	75000	29400	148900	3770900
30	1500	75000	29400	138500	3909400
TOTAL	50000	2500000	979500	3909400	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				3.99	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				1.56	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				2223900	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				2.27	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.89	

Table A-106

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 834500

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	98100	417800	417800
17	5000	250000	98100	406200	824000
18	5000	250000	98100	394600	1218600
19	5000	250000	98100	383100	1601700
20	5000	250000	98100	371500	1973200
21	3500	175000	68700	318800	2292000
22	3500	175000	68700	307200	2599200
23	3500	175000	68700	295600	2894800
24	3500	175000	68700	284100	3178900
25	3500	175000	68700	272500	3451400
26	1500	75000	29400	198100	3649500
27	1500	75000	29400	186600	3836100
28	1500	75000	29400	175000	4011100
29	1500	75000	29400	163400	4174500
30	1500	75000	29400	151900	4326400
TOTAL	50000	2500000	981000	4326400	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	4.41
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.73
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	2464300
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.51
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.99

Table A-107

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 5.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 908300

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	98200	456900	456900
17	5000	250000	98200	444300	901200
18	5000	250000	98200	431700	332900
19	5000	250000	98200	419100	1752000
20	5000	250000	98200	406500	2158500
21	3500	175000	68800	347400	2505900
22	3500	175000	68800	334800	2840700
23	3500	175000	68800	322200	3162900
24	3500	175000	68800	309600	3472500
25	3500	175000	68800	297000	3769500
26	1500	75000	29500	214300	3983800
27	1500	75000	29500	201700	4185500
28	1500	75000	29500	189100	4374600
29	1500	75000	29500	176500	4551100
30	1500	75000	29500	163900	4715000
TOTAL	50000	2500000	982500	4715000	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	4.80
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.89
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	2689400
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.74
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.08

Table A-108

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 6.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 974900

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	98400	493400	493400
17	5000	250000	98400	479900	973300
18	5000	250000	98400	466300	1439600
19	5000	250000	98400	452800	1892400
20	5000	250000	98400	439300	2331700
21	3500	175000	68900	374400	2706100
22	3500	175000	68900	360900	3067000
23	3500	175000	68900	347300	3414300
24	3500	175000	68900	333800	3748100
25	3500	175000	68900	320300	4068400
26	1500	75000	29500	229700	4298100
27	1500	75000	29500	216200	4514300
28	1500	75000	29500	202600	4716900
29	1500	75000	29500	189100	4906000
30	1500	75000	29500	175600	5081600
TOTAL	50000	2500000	984000	5081600	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				5.16	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				2.03	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				2901100	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				2.95	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				1.16	

Table A-109

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 7.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1036300

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	98500	528300	528300
17	5000	250000	98500	513900	1042200
18	5000	250000	98500	499500	1541700
19	5000	250000	98500	485100	2026800
20	5000	250000	98500	470800	2497600
21	3500	175000	69000	399800	2897400
22	3500	175000	69000	385400	3282800
23	3500	175000	69000	371000	3653800
24	3500	175000	69000	356700	4010500
25	3500	175000	69000	342300	4352800
26	1500	75000	29600	243900	4596700
27	1500	75000	29600	229500	4826200
28	1500	75000	29600	215200	5041400
29	1500	75000	29600	20080	5242200
30	1500	75000	29600	186400	5428600
TOTAL	50000	2500000	985500	5428600	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	5.51
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	2.17
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	3102100
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	3.15
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.24

Table A-110

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1280100

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	293800	634300	634300
17	5000	750000	293800	616500	1250800
18	5000	750000	293800	598800	1849600
19	5000	750000	293800	581000	2430600
20	5000	750000	293800	563300	2993900
21	3500	525000	205700	478500	3472400
22	3500	525000	205700	460800	3933200
23	3500	525000	205700	443100	4376300
24	3500	525000	205700	425300	4801600
25	3500	525000	205700	407600	5209200
26	1500	225000	88100	291400	5500600
27	1500	225000	88100	273700	5774300
28	1500	225000	88100	256000	6030300
29	1500	225000	88100	238200	6268500
30	1500	225000	88100	220500	6489000
TOTAL	50000	7500000	2938000	6489000	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	2.21
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	0.87
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	3712400
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.26
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.49

Table A-111

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1431500

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	294200	729300	729300
17	5000	750000	294200	709400	1438700
18	5000	750000	294200	689600	2128300
19	5000	750000	294200	669700	2798000
20	5000	750000	294200	649900	3447900
21	3500	525000	206000	547700	3995600
22	3500	525000	206000	527900	4523500
23	3500	525000	206000	508000	5031500
24	3500	525000	206000	488200	5519700
25	3500	525000	206000	468400	5988100
26	1500	225000	88300	329700	6317800
27	1500	225000	88300	309900	6627700
28	1500	225000	88300	290000	6917700
29	1500	225000	88300	270200	7187900
30	1500	225000	88300	250300	7438200
TOTAL	50000	7500000	2942500	7438200	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	2.53
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	0.99
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	4262400
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.45
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.57

Table A-112

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 5.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1568800

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	294700	819300	819300
17	5000	750000	294700	797600	1616900
18	5000	750000	294700	775800	2392700
19	5000	750000	294700	754000	3146700
20	5000	750000	294700	732300	3879000
21	3500	525000	206300	613300	4492300
22	3500	525000	206300	591600	5083900
23	3500	525000	206300	569800	5653700
24	3500	525000	206300	548100	6201800
25	3500	525000	206300	526300	6728100
26	1500	225000	88400	365400	7093500
27	1500	225000	88400	343700	7437200
28	1500	225000	88400	321900	7759100
29	1500	225000	88400	300200	8059300
30	1500	225000	88400	278400	8337700
TOTAL	50000	7500000	2947000	8337700	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				2.83	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				1.11	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				4784000	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.62	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.64	

Table A-113

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 6.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1694400

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	295100	905800	905800
17	5000	750000	295100	882300	1788100
18	5000	750000	295100	858800	2646900
19	5000	750000	295100	835300	3482200
20	5000	750000	295100	811800	4294000
21	3500	525000	206600	676000	4970000
22	3500	525000	206600	652500	5622500
23	3500	525000	206600	629000	6251500
24	3500	525000	206600	605500	6857000
25	3500	525000	206600	582000	7439000
26	1500	225000	88500	399300	7838300
27	1500	225000	88500	375800	8214100
28	1500	225000	88500	352300	8566400
29	1500	225000	88500	328800	8895200
30	1500	225000	88500	305300	9200500
TOTAL	50000	7500000	2951000	9200500	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				3.12	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				1.23	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				5284900	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.79	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.70	

Table A-114

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 7.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1808000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	295600	988800	988800
17	5000	750000	295600	963700	1952500
18	5000	750000	295600	938600	2891100
19	5000	750000	295600	913600	3804700
20	5000	750000	295600	888500	4693200
21	3500	525000	206900	736200	5429400
22	3500	525000	206900	711200	6140600
23	3500	525000	206900	686100	6826700
24	3500	525000	206900	661100	7487800
25	3500	525000	206900	636000	8123800
26	1500	225000	88700	431400	8555200
27	1500	225000	88700	406400	8961600
28	1500	225000	88700	381300	9342900
29	1500	225000	88700	356200	9699100
30	1500	225000	88700	331200	10030300
TOTAL	50000	7500000	2956000	10030300	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				3.39	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				1.34	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				5766600	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.95	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.77	

Table A-115

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1695100

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	489700	857200	857200
17	5000	1250000	489700	833700	1690900
18	5000	1250000	489700	810200	2501100
19	5000	1250000	489700	786700	3287800
20	5000	1250000	489700	763200	4051000
21	3500	875000	342800	642200	4693200
22	3500	875000	342800	618700	5311900
23	3500	875000	342800	595200	5907100
24	3500	875000	342800	571600	6478700
25	3500	875000	342800	548100	7026800
26	1500	375000	146900	384800	7411600
27	1500	375000	146900	361300	7772900
28	1500	375000	146900	337800	8110700
29	1500	375000	146900	314300	8425000
30	1500	375000	146900	290800	8715800
TOTAL	50000	12500000	4897000	8715800	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	1.78
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	0.70
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	4999800
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.02
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.40

Table A-116

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1868100

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	490400	989600	989600
17	5000	1250000	490400	963700	1953300
18	5000	1250000	490400	937800	2891100
19	5000	1250000	490400	911900	3803000
20	5000	1250000	490400	886000	4689000
21	3500	875000	343300	738000	5427000
22	3500	875000	343300	712100	6139100
23	3500	875000	343300	686200	6825300
24	3500	875000	343300	660300	7485600
25	3500	875000	343300	634400	8120000
26	1500	375000	147100	435500	8555500
27	1500	375000	147100	409600	8965100
28	1500	375000	147100	383700	9348800
29	1500	375000	147100	357800	9706600
30	1500	375000	147100	331900	10038500
TOTAL	50000	12500000	4904000	10038500	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				2.05	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				0.80	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				5768300	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.18	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.46	

Table A-117

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 5.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2086100

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	491100	1136400	1136400
17	5000	1250000	491100	1107500	2243900
18	5000	1250000	491100	1078500	3322400
19	5000	1250000	491100	1049600	4372000
20	5000	1250000	491100	1020700	5392700
21	3500	875000	343800	844800	6237500
22	3500	875000	343800	815900	7053400
23	3500	875000	343800	787000	7840400
24	3500	875000	343800	758000	8598400
25	3500	875000	343800	729100	9327500
26	1500	375000	147300	493400	9820900
27	1500	375000	147300	464400	10285300
28	1500	375000	147300	435500	10720800
29	1500	375000	147300	406600	11127400
30	1500	375000	147300	377600	11505000
TOTAL	50000	12500000	4911000	11505000	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				2.34	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				0.92	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				6619100	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.35	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.53	

Table A-118

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 6.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2253600

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	491900	1267700	1267700
17	5000	1250000	491900	1236500	2504200
18	5000	1250000	491900	1205300	3709500
19	5000	1250000	491900	1174000	4883500
20	5000	1250000	491900	1142800	6026300
21	3500	875000	344300	939900	6966200
22	3500	875000	344300	908700	7874900
23	3500	875000	344300	877500	8752400
24	3500	875000	344300	846200	9598600
25	3500	875000	344300	815000	10413600
26	1500	375000	147600	543500	10957100
27	1500	375000	147600	512300	11469400
28	1500	375000	147600	481000	11950400
29	1500	375000	147600	449800	12400200
30	1500	375000	147600	418600	12818800
TOTAL	50000	12500000	4919000	12818800	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED 2.61
EQUIVALENT COST, MILLS PER KILOWATT-HOUR 1.03
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS 7382400
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED 1.50
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR 0.59

Table A-119

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 7.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2407700

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	492600	1394700	1394700
17	5000	1250000	492600	1361300	2756000
18	5000	1250000	492600	1327900	4083900
19	5000	1250000	492600	1294500	5378400
20	5000	1250000	492600	1261200	6639600
21	3500	875000	344800	1031600	7671200
22	3500	875000	344800	998200	8669400
23	3500	875000	344800	964800	9634200
24	3500	875000	344800	931400	10565600
25	3500	875000	344800	898000	11463600
26	1500	375000	147800	591600	12055200
27	1500	375000	147800	558200	12613400
28	1500	375000	147800	524800	13138200
29	1500	375000	147800	491400	13629600
30	1500	375000	147800	458000	14087600
TOTAL	50000	12500000	4926000	14087600	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	2.86
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.13
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	8120000
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.65
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.65

Table A-120

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2032300

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	685600	1055400	1055400
17	5000	1750000	685600	1027200	2082600
18	5000	1750000	685600	999100	3081700
19	5000	1750000	685600	970900	4052600
20	5000	1750000	685600	942700	4995300
21	3500	1225000	479900	787200	5782500
22	3500	1225000	479900	759000	6541500
23	3500	1225000	479900	730800	7272300
24	3500	1225000	479900	702600	7974900
25	3500	1225000	479900	674500	8649400
26	1500	525000	205700	465900	9115300
27	1500	525000	205700	43 700	9553000
28	1500	525000	205700	409500	9962500
29	1500	525000	205700	381300	10343800
30	1500	525000	205700	353100	10696900
TOTAL	50000	17500000	6856000	10696900	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED 1.56

EQUIVALENT COST, MILLS PER KILOWATT-HOUR 0.61

PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS 6146600

EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED 0.90

EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR 0.35

Table A-121

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2278800

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	686600	1242200	1242200
17	5000	1750000	686600	1210600	2452800
18	5000	1750000	686600	1179000	3631800
19	5000	1750000	686600	1147400	4779200
20	5000	1750000	686600	1115800	5895000
21	3500	1225000	480600	922400	6817400
22	3500	1225000	480600	890800	7708200
23	3500	1225000	480600	859200	8567400
24	3500	1225000	480600	827600	9395000
25	3500	1225000	480600	796000	10191000
26	1500	525000	206000	537500	10728500
27	1500	525000	206000	505900	11234400
28	1500	525000	206000	474300	11708700
29	1500	525000	206000	442800	12151500
30	1500	525000	206000	411200	12562700
TOTAL	50000	17500000	6866000	12562700	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				1.83	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				0.72	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				7230600	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.05	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.41	

Table A-122

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 5.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2503200

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	687600	1421900	1421900
17	5000	1750000	687600	1387200	2809100
18	5000	1750000	687600	1352400	4161500
19	5000	1750000	687600	1317700	5479200
20	5000	1750000	687600	1283000	6762200
21	3500	1225000	481300	1052200	7814400
22	3500	1225000	481300	1017500	8831900
23	3500	1225000	481300	982800	9814700
24	3500	1225000	481300	948000	10762700
25	3500	1225000	481300	913300	11676000
26	1500	525000	206300	605800	12281800
27	1500	525000	206300	571100	12852900
28	1500	525000	206300	536400	13389300
29	1500	525000	206300	501700	13891000
30	1500	525000	206300	467000	14358000
TOTAL	50000	17500000	6876000	14358000	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				2.09	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				0.82	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				8274100	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.20	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.47	

Table A-123

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 6.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2707700

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	688600	1595800	1595800
17	5000	1750000	688600	1558300	3154100
18	5000	1750000	688600	1520700	4674800
19	5000	1750000	688600	1483200	6158000
20	5000	1750000	688600	1445600	7603600
21	3500	1225000	482000	1177900	8781500
22	3500	1225000	482000	1140300	9921800
23	3500	1225000	482000	1102800	11024600
24	3500	1225000	482000	1065200	12089800
25	3500	1225000	482000	1027700	13117500
26	1500	525000	206600	670900	13788400
27	1500	525000	206600	633300	14421700
28	1500	525000	206600	595800	15017500
29	1500	525000	206600	558200	15575700
30	1500	525000	206600	520700	16096400
TOTAL	50000	17500000	6886000	16096400	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	2.34
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	0.92
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	9285400
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.35
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.53

Table A-124

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 0.8% S IN FUEL, 7.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2893300

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	689600	1776900	1776900
17	5000	1750000	689600	1736800	3513700
18	5000	1750000	689600	1696700	5210400
19	5000	1750000	689600	1656500	6866900
20	5000	1750000	689600	1616400	8483300
21	3500	1225000	482800	1309600	9792900
22	3500	1225000	482800	1269500	11062400
23	3500	1225000	482800	1229300	12291700
24	3500	1225000	482800	1189200	13480900
25	3500	1225000	482800	1149100	14630000
26	1500	525000	206900	740300	15370300
27	1500	525000	206900	700200	16070500
28	1500	525000	206900	660000	16730500
29	1500	525000	206900	619900	17350400
30	1500	525000	206900	579800	17930200
TOTAL	5000C	17500000	6896500	17930200	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				2.60	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				1.02	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				10347900	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.50	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.59	

Table A-125

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 1.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 817100

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	98000	407900	407900
17	5000	250000	98000	396500	804400
18	5000	250000	98000	385200	1189600
19	5000	250000	98000	373800	1563400
20	5000	250000	98000	362500	1925900
21	3500	175000	68600	311600	2237500
22	3500	175000	68600	300200	2537700
23	3500	175000	68600	288900	2826600
24	3500	175000	68600	277600	3104200
25	3500	175000	68600	266200	3370400
26	1500	75000	29400	194000	3564400
27	1500	75000	29400	182700	3747100
28	1500	75000	29400	171300	3918400
29	1500	75000	29400	160000	4078400
30	1500	75000	29400	148700	4227100
TOTAL	50000	2500000	980000	4227100	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	4.31
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.69
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	2406900
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.46
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.96

Table A-126

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 2.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1070500

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	98400	546100	546100
17	5000	250000	98400	531200	1077300
18	5000	250000	98400	516400	1593700
19	5000	250000	98400	501500	2095200
20	5000	250000	98400	486700	2581900
21	3500	175000	68900	412900	2994800
22	3500	175000	68900	398100	3392900
23	3500	175000	68900	383200	3776100
24	3500	175000	68900	368400	4144500
25	3500	175000	68900	353500	4498000
26	1500	75000	29500	251600	4749600
27	1500	75000	29500	236700	4986300
28	1500	75000	29500	221800	5208100
29	1500	75000	29500	207000	5415100
30	1500	75000	29500	192100	5607200
TOTAL	50000	2500000	984000	5607200	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	5.70
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	2.24
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	3205200
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	3.26
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.28

Table A-127

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1271500

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	98900	668100	668100
17	5000	250000	98900	650400	1318500
18	5000	250000	98900	632800	1951300
19	5000	250000	98900	615200	2566500
20	5000	250000	98900	597500	3164000
21	3500	175000	69200	502100	3666100
22	3500	175000	69200	484400	4150500
23	3500	175000	69200	466800	4617300
24	3500	175000	69200	449200	5066500
25	3500	175000	69200	431500	5498000
26	1500	75000	29700	301000	5799000
27	1500	75000	29700	283300	6082300
28	1500	75000	29700	265700	6348000
29	1500	75000	29700	248100	6596100
30	1500	75000	29700	230400	6826500
TOTAL	50000	2500000	989000	6826500	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED 6.90
EQUIVALENT COST, MILLS PER KILOWATT-HOUR 2.73
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS 3911300
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED 3.95
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR 1.56

Table A-128

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1442000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	99400	781000	781000
17	5000	250000	99400	761000	1542000
18	5000	250000	99400	741100	2283100
19	5000	250000	99400	721100	3004200
20	5000	250000	99400	701100	3705300
21	3500	175000	69600	584200	4289500
22	3500	175000	69600	564200	4853700
23	3500	175000	69600	544200	5397900
24	3500	175000	69600	524200	5922100
25	3500	175000	69600	504200	6426300
26	1500	75000	29800	345700	6772000
27	1500	75000	29800	325800	7097800
28	1500	75000	29800	305800	7403600
29	1500	75000	29800	285800	7689400
30	1500	75000	29800	265800	7955200
TOTAL	50000	2500000	994000	7955200	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				8.00	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				3.18	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				4565900	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				4.59	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				1.83	

Table A-129

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 1.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1404600

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	293900	707400	707400
17	5000	750000	293900	687900	1395300
18	5000	750000	293900	668400	2063700
19	5000	750000	293900	649000	2712700
20	5000	750000	293900	629500	3342200
21	3500	525000	205700	532000	3874200
22	3500	525000	205700	512500	4386700
23	3500	525000	205700	493100	4879800
24	3500	525000	205700	473600	5353400
25	3500	525000	205700	454100	5807500
26	1500	225000	88200	321600	6129100
27	1500	225000	88200	302100	6431200
28	1500	225000	88200	282600	6713800
29	1500	225000	88200	263200	6977000
30	1500	225000	88200	243700	7220700
TOTAL	50000	7500000	2939000	7220700	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				2.46	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				0.96	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				4135700	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.41	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.55	

Table A-130

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 2.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1874200

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	295300	1029400	1029400
17	5000	750000	295300	1003500	2032900
18	5000	750000	295300	977500	3010400
19	5000	750000	295300	951500	3961900
20	5000	750000	295300	925500	4887400
21	3500	525000	206700	766200	5653600
22	3500	525000	206700	740300	6393900
23	3500	525000	206700	714300	7108200
24	3500	525000	206700	688300	7796500
25	3500	525000	206700	662300	8458800
26	1500	225000	88600	447800	8906600
27	1500	225000	88600	421900	9328500
28	1500	225000	88600	395900	9724400
29	1500	225000	88600	369900	10094300
30	1500	225000	88600	343900	10438200
TOTAL	50000	7500000	2953000	10438200	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				3.53	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				1.39	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				6002800	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				2.03	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.80	

Table A-131

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2251400

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	296700	1324800	1324800
17	5000	750000	296700	1293600	2618400
18	5000	750000	296700	1262300	3880700
19	5000	750000	296700	1231100	5111800
20	5000	750000	296700	1199900	6311700
21	3500	525000	207700	979700	7291400
22	3500	525000	207700	948500	8239900
23	3500	525000	207700	917200	9157100
24	3500	525000	207700	886000	10043100
25	3500	525000	207700	854800	10897900
26	1500	225000	89000	560600	11458500
27	1500	225000	89000	529400	11987900
28	1500	225000	89000	498100	12486000
29	1500	225000	89000	466900	12952900
30	1500	225000	89000	435700	13388600
TOTAL	50000	7500000	2967000	13388600	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				4.51	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				1.79	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				7717400	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				2.60	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				1.03	

Table A-132

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2574200

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	298200	1604200	1604200
17	5000	750000	298200	1568500	3172700
18	5000	750000	298200	1532800	4705500
19	5000	750000	298200	1497200	6202700
20	5000	750000	298200	1461500	7664200
21	3500	525000	208700	1181300	8845500
22	3500	525000	208700	1145600	9991100
23	3500	525000	208700	1109900	11101000
24	3500	525000	208700	1074200	12175200
25	3500	525000	208700	1038500	13213700
26	1500	225000	89500	665000	13878700
27	1500	225000	89500	629300	14508000
28	1500	225000	89500	593600	15101600
29	1500	225000	89500	557900	15659500
30	1500	225000	89500	522200	16181700
TOTAL	50000	7500000	2982000	16181700	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	5.43
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	2.16
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	9342200
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	3.13
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.25

Table A-133

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 1.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1865600

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	489800	966600	966600
17	5000	1250000	489800	940800	1907400
18	5000	1250000	489800	914900	2822300
19	5000	1250000	489800	889000	3711300
20	5000	1250000	489800	863100	4574400
21	3500	875000	342900	722000	5296400
22	3500	875000	342900	696100	5992500
23	3500	875000	342900	670200	6662700
24	3500	875000	342900	644300	7307000
25	3500	875000	342900	618500	7925500
26	1500	375000	147000	428400	8353900
27	1500	375000	147000	402500	8756400
28	1500	375000	147000	376600	9133000
29	1500	375000	147000	350800	9483800
30	1500	375000	147000	324900	9808700
TOTAL	50000	12500000	4898500	9808700	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	2.00
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	0.78
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	5633500
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.15
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.45

Table A-134

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 2.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2498900

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	492200	1456800	1456800
17	5000	1250000	492200	1422100	2878900
18	5000	1250000	492200	1387500	4266400
19	5000	1250000	492200	1352800	5619200
20	5000	1250000	492200	1318200	6937400
21	3500	875000	344500	1076800	8014200
22	3500	875000	344500	1042200	9056400
23	3500	875000	344500	1007500	10063900
24	3500	875000	344500	972800	11036700
25	3500	875000	344500	938200	11974900
26	1500	375000	147700	615900	12590800
27	1500	375000	147700	581300	13172100
28	1500	375000	147700	546600	13718700
29	1500	375000	147700	512000	14230700
30	1500	375000	147700	477300	14708000
TOTAL	50000	12500000	4922000	14708000	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	2.99
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.18
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	8480000
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.72
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.68

Table A-135

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 3011400

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	494600	1924400	1924400
17	5000	1250000	494600	1882600	3807000
18	5000	1250000	494600	1840800	5647800
19	5000	1250000	494600	1799100	7446900
20	5000	1250000	494600	1757300	9204200
21	3500	875000	346200	1414900	10619100
22	3500	875000	346200	1373200	11992300
23	3500	875000	346200	1331400	13323700
24	3500	875000	346200	1289600	14613300
25	3500	875000	346200	1247900	15861200
26	1500	375000	148400	792100	16653300
27	1500	375000	148400	750300	17403600
28	1500	375000	148400	708600	18112200
29	1500	375000	148400	666800	18779000
30	1500	375000	148400	625000	19404000
TOTAL	50000	12500000	4946000	19404000	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	3.92
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.55
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	11207900
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.27
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.90

Table A-136

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 3498000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	497000	2380700	2380700
17	5000	1250000	497000	2332200	4712900
18	5000	1250000	497000	2283700	6996600
19	5000	1250000	497000	2235200	9231800
20	5000	1250000	497000	2186700	11418500
21	3500	875000	347900	1743400	13161900
22	3500	875000	347900	1694900	14856800
23	3500	875000	347900	1646300	16503100
24	3500	875000	347900	1597800	18100900
25	3500	875000	347900	1549300	19650200
26	1500	375000	149100	960100	20610300
27	1500	375000	149100	911600	21521900
28	1500	375000	149100	863100	22385000
29	1500	375000	149100	814600	23199600
30	1500	375000	149100	766100	23965700
TOTAL	[illegible]000	12500000	4970000	23965700	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	4.82
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.92
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	13863600
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.79
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.11

Table A-137

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 1.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2238600

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	685600	1197900	1197900
17	5000	1750000	685800	1166900	2364800
18	5000	1750000	685800	1135900	3500700
19	5000	1750000	685800	1104800	4605500
20	5000	1750000	685800	1073800	5679300
21	3500	1225000	480000	890800	6570100
22	3500	1225000	480000	859700	7429800
23	3500	1225000	480000	828700	8258500
24	3500	1225000	480000	797700	9056200
25	3500	1225000	480000	766600	9822800
26	1500	525000	205700	521700	10344500
27	1500	525000	205700	490700	10835200
28	1500	525000	205700	459600	11294800
29	1500	525000	205700	428600	11723400
30	1500	525000	205700	397600	12121000

TOTAL	5000C	17500000	6857500	12121000	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				1.77	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				0.69	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				6973000	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.02	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.40	

Table A-138

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 2.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 3005900

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	689100	1858900	1858900
17	5000	1750000	689100	1817200	3676100
18	5000	1750000	689100	1775600	5451700
19	5000	1750000	689100	1733900	7185600
20	5000	1750000	689100	1692200	8877800
21	3500	1225000	482300	1369300	10247100
22	3500	1225000	482300	1327600	11574700
23	3500	1225000	482300	1285900	12860600
24	3500	1225000	482300	1244300	14104900
25	3500	1225000	482300	1202600	15307500
26	1500	525000	206700	772200	16079700
27	1500	525000	206700	730500	16810200
28	1500	525000	206700	688900	17499000
29	1500	525000	206700	647100	18146100
30	1500	525000	206700	605500	18751600
TOTAL	50000	17500000	6890500	18751600	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	2.72
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.07
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	10824500
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.57
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.62

Table A-139

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 3676800

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	692400	2501700	2501700
17	5000	1750000	692400	2450700	4952400
18	5000	1750000	692400	2399700	7352100
19	5000	1750000	692400	2348700	9700800
20	5000	1750000	692400	2297800	11998600
21	3500	1225000	484700	1833200	13831800
22	3500	1225000	484700	1782200	15614000
23	3500	1225000	484700	1731200	17345200
24	3500	1225000	484700	1680200	19025400
25	3500	1225000	484700	1629200	20654600
26	1500	525000	207700	1010900	21665500
27	1500	525000	207700	959900	22625400
28	1500	525000	207700	908900	23534300
29	1500	525000	207700	857900	24392200
30	1500	525000	207700	806900	25199100
TOTAL	50000	17500000	6924000	25199100	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	3.64
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.44
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	14573700
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.10
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.83

Table A-140

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 3.0% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 4262100

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	695800	3108900	3108900
17	5000	1750000	695800	3049800	6158700
18	5000	1750000	695800	2990700	9149400
19	5000	1750000	695800	2931600	12081000
20	5000	1750000	695800	2872500	14953500
21	3500	1225000	487000	2268900	17222400
22	3500	1225000	487000	2209800	19432200
23	3500	1225000	487000	2150700	21582900
24	3500	1225000	487000	2091600	23674500
25	3500	1225000	487000	2032500	25707000
26	1500	525000	208700	1230400	26937400
27	1500	525000	208700	1171300	28108700
28	1500	525000	208700	1112200	29220900
29	1500	525000	208700	1053100	30274000
30	1500	525000	208700	994000	31268000
TOTAL	50000	17500000	6957500	31268000	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED 4.49
EQUIVALENT COST, MILLS PER KILOWATT-HOUR 1.79
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS 18110200
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED 2.60
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR 1.03

Table A-141

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 1.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 995300

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	98300	502600	502600
17	5000	250000	98300	488800	991400
18	5000	250000	98300	475000	1466400
19	5000	250000	98300	461200	1927600
20	5000	250000	98300	447400	2375000
21	3500	175000	68800	381000	2756000
22	3500	175000	68800	367200	3123200
23	3500	175000	68800	353300	3476500
24	3500	175000	68800	339500	3816000
25	3500	175000	68800	325700	4141700
26	1500	75000	29500	233700	4375400
27	1500	75000	29500	219900	4595300
28	1500	75000	29500	206100	4801400
29	1500	75000	29500	192300	4993700
30	1500	75000	29500	178500	5172200
TOTAL	50000	2500000	983000	5172200	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	5.26
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	2.07
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	2953500
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	3.00
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.18

Table A-142

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 2.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1332900

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	99100	707500	707500
17	5000	250000	99100	689100	1396600
18	5000	250000	99100	670600	2067200
19	5000	250000	99100	652100	2719300
20	5000	250000	99100	633600	3352900
21	3500	175000	69400	530600	3883500
22	3500	175000	69400	512100	4395600
23	3500	175000	69400	493600	4889200
24	3500	175000	69400	475100	5364300
25	3500	175000	69400	456600	5820900
26	1500	75000	29700	316600	6137500
27	1500	75000	29700	298100	6435600
28	1500	75000	29700	279600	6715200
29	1500	75000	29700	261200	6976400
30	1500	75000	29700	242700	7219100
TOTAL	50000	2500000	991000	7219100	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	7.28
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	2.89
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	4139200
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	4.18
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.66

Table A-143

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1602600

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	99900	892400	892400
17	5000	250000	99900	870200	1762600
18	5000	250000	99900	848000	2610600
19	5000	250000	99900	825800	3436400
20	5000	250000	99900	803600	4240000
21	3500	175000	69900	665000	4905000
22	3500	175000	69900	642800	5547800
23	3500	175000	69900	620500	6168300
24	3500	175000	69900	598300	6766600
25	3500	175000	69900	576100	7342700
26	1500	75000	30000	389300	7732000
27	1500	75000	30000	367100	8099100
28	1500	75000	30000	344900	8444000
29	1500	75000	30000	322700	8766700
30	1500	75000	30000	300400	9067100
TOTAL	50000	2500000	999000	9067100	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				9.08	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				3.63	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				5211300	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				5.22	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				2.08	

Table A-144

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 50 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1838700

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	250000	100700	1068700	1068700
17	5000	250000	100700	1043200	2111900
18	5000	250000	100700	1017700	3129600
19	5000	250000	100700	992200	4121800
20	5000	250000	100700	966700	5088500
21	3500	175000	70500	792900	5881400
22	3500	175000	70500	767400	6648800
23	3500	175000	70500	741900	7390700
24	3500	175000	70500	716400	8107100
25	3500	175000	70500	690900	8798000
26	1500	75000	30200	457500	9255500
27	1500	75000	30200	432000	9687500
28	1500	75000	30200	406500	10094000
29	1500	75000	30200	381000	10475000
30	1500	75000	30200	355500	10830500
TOTAL	50000	2500000	1007000	10830500	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED 10.76

EQUIVALENT COST, MILLS PER KILOWATT-HOUR 4.33

PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS 6235100

EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED 6.19

EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR 2.49

Table A-145

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 1.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 1736200

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	294800	928000	928000
17	5000	750000	294800	904000	1832000
18	5000	750000	294800	879900	2711900
19	5000	750000	294800	855800	3567700
20	5000	750000	294800	831800	4399500
21	3500	525000	206400	692600	5092100
22	3500	525000	206400	668500	5760600
23	3500	525000	206400	644500	6405100
24	3500	525000	206400	620400	7025500
25	3500	525000	206400	596300	7621800
26	1500	225000	88500	408500	8030300
27	1500	225000	88500	384400	8414700
28	1500	225000	88500	360300	8775000
29	1500	225000	88500	336300	9111300
30	1500	225000	88500	312200	9423500
TOTAL	50000	7500000	2948500	9423500	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	3.20
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.26
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	5413800
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.84
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.72

Table A-146

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 2.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2369500

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	297200	1420300	1420300
17	5000	750000	297200	1387400	2807700
18	5000	750000	297200	1354500	4162200
19	5000	750000	297200	1321700	5483900
20	5000	750000	297200	1288800	6772700
21	3500	525000	208100	1048700	7821400
22	3500	525000	208100	1015900	8837300
23	3500	525000	208100	983000	9820300
24	3500	525000	208100	950100	10770400
25	3500	525000	208100	917300	11687700
26	1500	225000	89200	596500	12284200
27	1500	225000	89200	563700	12847900
28	1500	225000	89200	530800	13378700
29	1500	225000	89200	497900	13876600
30	1500	225000	89200	465100	14341700
TOTAL	50000	7500000	2972500	14341700	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	4.82
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.91
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	8271800
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.78
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.10

Table A-147

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2926600

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	299700	1914300	1914300
17	5000	750000	299700	1873800	3788100
18	5000	750000	299700	1833200	5621300
19	5000	750000	299700	1792600	7413900
20	5000	750000	299700	1752000	9165900
21	3500	525000	209800	1406500	10572400
22	3500	525000	209800	1365900	11938300
23	3500	525000	209800	1325400	13263700
24	3500	525000	209800	1284800	14548500
25	3500	525000	209800	1244200	15792700
26	1500	225000	89900	783400	16576100
27	1500	225000	89900	742800	17318900
28	1500	225000	89900	702300	18021200
29	1500	225000	89900	661700	18682900
30	1500	225000	89900	621100	19304000
TOTAL	50000	7500000	2997000	19304000	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	6.44
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	2.57
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	11153800
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	3.72
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.49

Table A-148

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 150 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 3376200

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	750000	302100	2362800	2362800
17	5000	750000	302100	2316000	4678800
18	5000	750000	302100	2269200	6948000
19	5000	750000	302100	2222400	9170400
20	5000	750000	302100	2175600	11346000
21	3500	525000	211500	1728700	13074700
22	3500	525000	211500	1681900	14756600
23	3500	525000	211500	1635100	16391700
24	3500	525000	211500	1588300	17980000
25	3500	525000	211500	1541500	19521500
26	1500	225000	90600	946900	20468400
27	1500	225000	90600	900100	21368500
28	1500	225000	90600	853300	22221800
29	1500	225000	90600	806500	23028300
30	1500	225000	90600	759700	23788000
TOTAL	50000	7500000	3021000	23788000	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED 7.87
EQUIVALENT COST, MILLS PER KILOWATT-HOUR 3.17
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS 13765400
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED 4.56
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR 1.84

Table A-149

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 1.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2314500

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	491400	1301100	1301100
17	5000	1250000	491400	1269000	2570100
18	5000	1250000	491400	1236900	3807000
19	5000	1250000	491400	1204800	5011800
20	5000	1250000	491400	1172700	6184500
21	3500	875000	344000	964400	7148900
22	3500	875000	344000	932300	8081200
23	3500	875000	344000	900300	8981500
24	3500	875000	344000	868200	9849700
25	3500	875000	344000	836100	10685800
26	1500	375000	147400	557500	11243300
27	1500	375000	147400	525400	11768700
28	1500	375000	147400	493300	12262000
29	1500	375000	147400	461200	12723200
30	1500	375000	147400	429100	13152300
TOTAL	50000	12500000	4914000	13152300	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				2.68	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				1.05	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				7575100	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				1.54	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				0.61	

Table A-150

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 2.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 3221100

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	495400	2095700	2095700
17	5000	1250000	495400	2051000	4146700
18	5000	1250000	495400	2006400	6153100
19	5000	1250000	495400	1961700	8114800
20	5000	1250000	495400	1917100	10031900
21	3500	875000	346800	1539000	11570900
22	3500	875000	346800	1494300	13065200
23	3500	875000	346800	1449700	14514900
24	3500	875000	346800	1405000	15919900
25	3500	875000	346800	1360400	17280300
26	1500	375000	148600	857000	18137300
27	1500	375000	148600	812400	18949700
28	1500	375000	148600	767700	19717400
29	1500	375000	148600	723000	20440400
30	1500	375000	148600	678400	21118800
TOTAL	50000	12500000	4954000	21118800	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	4.26
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.69
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	12204500
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.46
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.98

Table A-151

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 3968400

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15				2838200	2838200
16	5000	1250000	499400	2783200	5621400
17	5000	1250000	499400	2728200	8349600
18	5000	1250000	499400	2673100	11022700
19	5000	1250000	499400	2618100	13640800
20	5000	1250000	499400	2072300	15713100
21	3500	875000	349600	2017300	17730400
22	3500	875000	349600	1962300	19692700
23	3500	875000	349600	1907200	21599900
24	3500	875000	349600	1852200	23452100
25	3500	875000	349600	1127100	24579200
26	1500	375000	149800	1072000	25651200
27	1500	375000	149800	1017000	26668200
28	1500	375000	149800	961900	27630100
29	1500	375000	149800	906900	28537000
30	1500	375000	149800		
TOTAL	50000	12500000	4994000	28537000	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				5.71	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				2.28	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				16526400	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				3.31	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				1.32	

Table A-152

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 250 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 4582000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1250000	503500	3556600	3556600
17	5000	1250000	503500	3493000	7049600
18	5000	1250000	503500	3429500	10479100
19	5000	1250000	503500	3365900	13845000
20	5000	1250000	503500	3302400	17147400
21	3500	875000	352500	2588200	19735600
22	3500	875000	352500	2524700	22260300
23	3500	875000	352500	2461100	24721400
24	3500	875000	352500	2397600	27119000
25	3500	875000	352500	2334100	29453100
26	1500	375000	151100	1384900	30838000
27	1500	375000	151100	1321400	32159400
28	1500	375000	151100	1257800	33417200
29	1500	375000	151100	1194300	34611500
30	1500	375000	151100	1130700	35742200
TOTAL	50000	12500000	5035500	35742200	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	7.10
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	2.86
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	20723500
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	4.12
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.66

Table A-153

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 1.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 2782700

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	688000	1639600	1639600
17	5000	1750000	688000	1601000	3240600
18	5000	1750000	688000	1562400	4803000
19	5000	1750000	688000	1523800	6326800
20	5000	1750000	688000	1485300	7812100
21	3500	1225000	481600	1209900	9022000
22	3500	1225000	481600	1171300	10193300
23	3500	1225000	481600	1132700	11326000
24	3500	1225000	481600	1094100	12420100
25	3500	1225000	481600	1055500	13475600
26	1500	525000	206400	688800	14164400
27	1500	525000	206400	650200	14814600
28	1500	525000	206400	611600	15426200
29	1500	525000	206400	573000	15999200
30	1500	525000	206400	534400	16533600
TOTAL	50000	17500000	6880000	16533600	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	2.40
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	0.94
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	9538500
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	1.39
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.55

Table A-154

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 2.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 3927000

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	693600	2714000	2714000
17	5000	1750000	693600	2659600	5373600
18	5000	1750000	693600	2605100	7978700
19	5000	1750000	693600	2550700	10529400
20	5000	1750000	693600	2496200	13025600
21	3500	1225000	485500	1984700	15010300
22	3500	1225000	465500	1930300	16940600
23	3500	1225000	485500	1875800	18816400
24	3500	1225000	485500	1821400	20637800
25	3500	1225000	485500	1766900	22404700
26	1500	525000	208100	1087300	23492000
27	1500	525000	208100	1032800	24524800
28	1500	525000	208100	978400	25503200
29	1500	525000	208100	923900	26427100
30	1500	525000	208100	869500	27296600
TOTAL	50000	17500000	6936000	27296600	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	3.94
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	1.56
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	15799300
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	2.28
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	0.90

Table A-155

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 3.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 4766400

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	699200	3691200	3691200
17	5000	1750000	699200	3625100	7316300
18	5000	1750000	699200	3559000	10875300
19	5000	1750000	699200	3492900	14368200
20	5000	1750000	699200	3426800	17795000
21	3500	1225000	489400	2685700	20480700
22	3500	1225000	489400	2619600	23100300
23	3500	1225000	489400	2553500	25653800
24	3500	1225000	489400	2487400	28141200
25	3500	1225000	489400	2421300	30562500
26	1500	525000	209800	1437000	31999500
27	1500	525000	209800	1370900	33370400
28	1500	525000	209800	1304800	34675200
29	1500	525000	209800	1238700	35913900
30	1500	525000	209800	1172600	37086500
TOTAL	50000	17500000	6992000	37086500	
EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED				5.30	
EQUIVALENT COST, MILLS PER KILOWATT-HOUR				2.12	
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS				21504200	
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED				3.08	
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR				1.23	

Table A-156

DRY LIMESTONE INJECTION, REGULATED POWER CO. ECON., 350 MW EX. COAL FIRED POWER UNIT, 5.0% S IN FUEL, 4.0 INJECTION STOICHIOMETRY.

FIXED INVESTMENT: $ 5645500

YEARS AFTER POWER UNIT START	ANNUAL OPERATION, KW-HR/KW	POWER GENERATION M KWH/YR	POWER UNIT FUEL CONSUMPTION, TONS COAL/YR	ANNUAL OPERATING COST INCLUDING REGULATED ROI FOR POWER COMPANY (NET ANNUAL INCREASE IN COST OF POWER) $	CUMULATIVE NET INCREASE IN COST OF POWER, $
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16	5000	1750000	705000	4708000	4708000
17	5000	1750000	705000	4629700	9337700
18	5000	1750000	705000	4551400	13889100
19	5000	1750000	705000	4473100	18362200
20	5000	1750000	705000	4394800	22757000
21	3500	1225000	493500	3416000	26173000
22	3500	1225000	493500	3337700	29510700
23	3500	1225000	493500	3259400	32770100
24	3500	1225000	493500	3181100	35951200
25	3500	1225000	493500	3102800	39054000
26	1500	525000	211500	1802000	40856000
27	1500	525000	211500	1723700	42579700
28	1500	525000	211500	1645400	44225100
29	1500	525000	211500	1567100	45792200
30	1500	525000	211500	1488800	47281000
TOTAL	50000	17500000	7050000	47281000	

EQUIVALENT COST, DOLLARS PER TON OF COAL BURNED	6.71
EQUIVALENT COST, MILLS PER KILOWATT-HOUR	2.70
PRESENT WORTH IF DISCOUNTED AT 10.0% TO INITIAL YEAR, DOLLARS	27443100
EQUIVALENT PRESENT WORTH, DOLLARS PER TON OF COAL BURNED	3.89
EQUIVALENT PRESENT WORTH, MILLS PER KILOWATT-HOUR	1.57